The impact of supply chain management practice on construction project performance

By:

Jati Utomo Dwi Hatmoko

NEWCASTLE UNIVERSITY LIBRARY
207 32584 7
Thesis L8942

A thesis submitted for the degree of Doctor of Philosophy

School of Civil Engineering and Geosciences
Newcastle University
The United Kingdom
May 2008

Acknowledgement

I would like to express sincere appreciation to my supervisor, Dr. Stephen Scott, for his excellent guidance and assistance throughout this study. He has always provided valuable, challenging and constructive comments which have encourage me to improve my research skills and demonstrate the work precisely. These are reflected in this entire thesis.

I gratefully acknowledge the Technological and Professional Skills Development Sector Project (TPSDP) of Diponegoro University Semarang for granting me scholarship and to Civil Engineering Department, Diponegoro University Semarang for providing me the opportunity to pursue my educational goal.

I would like to thank to the contractors, subcontractors and suppliers who were willing to give their time for participating in this study. Many thanks are also expressed to colleagues and friends for their support and help during this study.

Finally I wish to dedicate this work to all my family, especially to my parents and my beloved wife, Anni, who have always given me endless encouragement and emotional support throughout this hardwork, and to my son, Baron, whose smile has always given me new energy and courage to complete this study as soon as possible.

Abstract

Construction supply chains encompass the flows of information, materials, labour, plant, equipment and temporary work, which originate from the different parties, viz., main contractors, suppliers, subcontractors and clients/architects. Any problems with these flows will eventually disrupt the project performance. The primary aim of this research was to gain a comprehensive understanding of the impact of supply chain management practice on construction project performance. The research methods adopted comprised: preliminary investigations, a main survey and the development of simulation models. The preliminary investigations were carried out by interviewing members of the construction industry and visiting two medium-sized building projects over a period of 6 months. The main survey was intended to collect data required for developing the simulation models. They were developed using Pertmaster Risk Expert™ software, which allows supply chain delays to be applied on a CPM network of a typical medium-sized building project of 300 days duration. The results of the simulation showed that when all work was carried out by the main contractor and all supply chain delays were applied, the project's median delay was 67 days (equivalent to 22% of the project duration). It was learnt that problems in material flow caused the biggest impact on the project, followed by labour flow, information flow, and 'plant, equipment and temporary work' flow. Among the problems in material flow, the biggest impact was due to difficulties in finding materials. When subcontractors were used for the activities that are normally subcontracted, there was a significant reduction of the median delays from 67 to 37 days (equivalent to a 45% reduction). These findings are an important measure of how much supply chain delays may impact on project performance and suggest that problems related to the supply chain in construction are likely to generate significant disruption.

Keywords: supply chain management, delays, risk, project performance, simulation

Table of contents

Acknowledgement ii

Abstract iii

Table of contents iv

List of tables viii

List of figures x

1 Introduction 1

1.1 Background 1

1.2 The gap in the research 2

1.3 Aims and Objectives 2

1.4 Scope of the research 3

1.5 Research Arrangement 3

1.6 Structure of the thesis 5

2 Literature Review 6

2.1 Supply chain management 6

2.1.1 Defining the supply chain 6

2.1.2 Defining supply chain management 8

2.1.3 Evolution of supply chain management 11

2.1.4 Development of supply chain management bodies of literature 13

2.1.5 SCM, logistics and purchasing 14

2.1.5.1 Logistics 14

2.1.5.2 Logistics and SCM 14

2.1.5.3 Purchasing 15

2.2 Supply chain management in construction 16

2.2.1 Why do we need to manage supply chains in construction? 18

2.2.2 Roles of SCM in Construction 19

2.2.3 Logistics in construction 20

2.2.4 Characteristic of construction supply chains 22

2.2.5 Stakeholders involved in construction supply chains 24

2.2.6 Problems in the construction industry and construction supply chains 27

2.3 Comparing SCM in manufacturing and construction 30

2.4 Measuring supply chains performance 32

2.4.1 Supply chain performance measurement in the manufacturing industry 32

2.4.2 Supply chains performance measurement in the construction industry 35

3 Research Methods 39

3.1 Overview of research methods 39

3.1.1 Exploratory, descriptive, analytical and predictive research 40

3.1.2 Qualitative and Quantitative Research 42

3.1.3 Deductive or inductive research 43

3.1.4 Applied or basic research 44

3.2 Simulation 44

3.2.1 Definitions 44

3.2.2 Uses and advantages of simulation 46
3.2.3 Classifications of systems and simulation 47
3.2.4 Steps in a simulation study 48
3.2.5 Comparing programming languages and simulation packages 50
3.2.6 Recent uses of simulation in research in the construction industry 50
3.3 Research methods adopted in the thesis 51
3.3.1 Preliminary Investigations 52
3.3.1.1 Interviews with members of the construction industry 52
3.3.1.2 Regular visits to construction projects 53
3.3.2 Main Survey 54
3.3.2.1 The respondents 54
3.3.2.2 Sending the questionnaires 54
3.4 Triangulation 54

4 The Investigations 56
4.1 Preliminary Investigations 56
4.1.1 Interviews with members of the construction industry 56
4.1.1.1 The companies and the interviewees 56
4.1.1.2 The questions 57
4.1.1.3 Lessons learnt from the interviews with members of the construction industry 57
4.1.2 Regular visits to construction projects 60
4.1.2.1 Project 1 (WBHS project) 61
A. Short description of the project 61
B. Lessons learnt from the WBHS project 61
4.1.2.2 Project 2 (ASC project) 65
A. Short description of the project 65
B. Lessons learnt from ASC project 65
4.2 The Main Survey 69
4.2.1 Developing the questionnaire 69
4.2.2 Testing the questionnaire 72
4.2.3 Results of the main survey 73
4.2.3.1 The responses 73
4.2.3.2 Grouping and labelling similar data 73
4.2.3.3 Removing invalid data 74
4.2.3.4 Mean as the representative of data set and the outliers 74

5 The Simulation Models 77
5.1 Developing the simulation models 77
5.1.1 Basic assumptions in the model 77
5.1.2 Defining the CPM network 79
5.1.3 Connecting supply chain delays to activities in the model 81
5.1.4 Arranging the positions of delays in the models 83
5.1.5 Combining delays 84
5.1.6 Modelling time buffers 85
5.1.7 Probabilistic branches 86
5.2 A brief discussion of Pertmaster Risk Expert™ v7.82 90
5.3 Running the simulations 92
5.3.1 Scenarios that can be tested 92
5.3.1.1 Optimistic and pessimistic versions 95
5.3.1.2 Provision of time buffers 97

5.3.2 Various simulation models 97
5.3.3 Defining the number of iterations 98
5.4 Model verification and validation 99
5.4.1 Model verification 99
5.4.2 Model validation 101
5.4.2.1 Animation 103
5.4.2.2 Event Validation 103
5.4.2.3 Extreme Condition Tests 103

6 Analysis and Discussion of the Results 105
6.1 The nature of the CPM network with SC delays 105
6.1.1 The paths through the network 105
6.1.2 Criticality and sensitivity of the activities 108
6.1.3 Mapping delays on the network 111
6.2 How the results are presented 114
6.3 Comparing the optimistic and the pessimistic versions 118
6.4 The provision of time buffers 123
6.4.1 Practical implications of providing time buffers in the project 128
6.5 Results of the simulations 129
6.5.1 Simulations where all the work is carried out by the main contractor 129
6.5.2 Simulations where subcontractors are used to carry out activities that are normally subcontracted 131
6.5.3 Understanding the results 134
6.5.3.1 P, E, C and median delays 134
6.5.3.2 Models with subcontractor delays 137
6.5.4 Implications of the results 140
6.5.4.1 All the work is carried out by the main contractor 140
6.5.4.2 Subcontractors are used to carry out activities that are normally subcontracted 143

7 Conclusions and Recommendations 144
7.1 Conclusions 144
7.2 Recommendations 146
7.2.1 Recommendations for the industry 146
7.2.2 Recommendations for further research 147

8 References 149

Appendices
Appendix A1: List of Questions for Main Contractor
Appendix A2: List of Questions for Subcontractor A1-1
Appendix A3: List of Questions for Material Suppliers A2-1
Appendix A4: Summary of the interviews with contractors, subcontractor and supplier in the UK (preliminary investigation) A3-1 A4-1
Appendix A5: Identification of delay factors
Appendix A6: The process of selecting the delays related to SCM, defining the impact and the operationalability A5-1 A6-1
Appendix A7: Cover letter and questionnaire for the main survey
Appendix A8: Detecting outliers with boxplot method A7-1
Appendix A9: Results of the main survey for the simulation A8-1
Appendix A10: The original CPM network with links added A9-1
Appendix A11: Matrix of activities and supply chain delays A10-1

Appendix B : Basic simulation models A11-1
Appendix C1: Various paths trough the CPM network, Total floats and potential delays B-1 C1-1
Appendix C2: Critical path, Criticality index and Duration sensitivity
Appendix C3: Histogram results C2-1
Appendix C4: Wilcoxon signed-ranks test results for model (1a/c) O/P_MC_All (TB) with various data size C3-1 C4-1
Appendix C5: Comparing subcontractor delays and delays they replaced C5-1

List of tables

Table 2-1 Supply chain definitions 6
Table 2-2 Different SCM labels (developed from Croom *et al.* (2000)) 9
Table 2-3 A sample of definitions of supply chain management (Croom et al., 2000) 9
Table 2-4 Categorisation of SCM (developed from Mentzer *et al.*(2001)) 10
Table 2-5 The evolution of SCM from the perspective of distribution and logistics (Rushton et al., 2000) 11
Table 2-6 Evolution of SCM from the perspective of management of production (Tan, 2001) 12
Table 2-7 Principal component bodies of supply chain literature (Croom et al., 2000) 13
Table 2-8 SCM definition in construction supply chain research 17
Table 2-9 The list of definitions of supply chain management (Vrijhoef, 1998) 17
Table 2-10 Stakeholders involved in the construction supply chain (Edum-Fotwe et al., 1999) 25
Table 2-11 Ten basic problems in contemporary construction supply chains (adapted from Vrijhoef (1998)) 29
Table 2-12 Comparison of traditional/manufacturing and construction supply chain (Ghurka, 2003) 31
Table 2-13 Measures of supply chain performance identified in the literature (Bhatnagar and Sohal, 2004) 32
Table 2-14 SCM performance measures (Beamon, 1999) 33
Table 2-15 Performance metrics of SCM base on six measurement perspectives (Otto and Kotzab, 2003) 34
Table 2-16 A framework for measuring SCM performance (Gunasekaran et al., 2004) 34
Table 2-17 Assessment efforts of construction supply chains (Vrijhoef, 1998) 35
Table 2-18 Key effectiveness measures (adapted from Al-Khalil *et al.* (2004)) 36
Table 2-19 Project supply chain performance metrics categories (Venkataraman, 2004) 37
Table 3-1 Classification of main types of research (Collis and Hussey, 2003) 40
Table 3-2 Classification of research methods according to research purpose (synthesized from Collis and Hussey (2003) and Ellram (1996)) 41
Table 3-3 Qualitative, quantitative and mixed method approaches (Creswell, 2003) 43
Table 3-4 Examples of application of simulation (adapted from Pidd (2004)) 46
Table 3-5 Four types triangulation (developed from Easterby-Smith *et al.* (1991)) 55
Table 4-1 Question areas for main contractor, subcontractor and supplier 57
Table 4-2 Meetings held in the WBHS project 62
Table 4-3 Delays identified from the WBHS project 63
Table 4-4 Coordination meetings held in the ASC project 65
Table 4-5 Delays identified in the ASC project 67
Table 4-6 Categorisation of delays related to supply chain issues which can be operationalised 72
Table 4-7 Results of the main survey for the simulation 76
Table 5-1 Various paths on the CPM network 79
Table 5-2 Matrix of activities and supply chain delays 82
Table 5-3 Assumptions of how supply chain delays impact on start date and duration of an activity 84

Table 5-4 Various scenarios to be tested 92
Table 5-5 Terms used for naming the models and associated delays or scenarios 93
Table 5-6 Basic models for all versions/scenarios 97
Table 5-7 Verification techniques (Law and Kelton, 2000) 100
Table 5-8 Techniques of validation (Sargent, 2003) 102
Table 6-1 Various paths through the CPM network, Total Floats and potential delays 107
Table 6-2 Comparison of mean and median of each histogram 116
Table 6-3 Optimistic and pessimistic models 118
Table 6-4 Wilcoxon signed-ranks test results for model (1a/c) O/P_MC_All (TB) 120
Table 6-5 Probabilities of occurrence of multiple delays 121
Table 6-6 Various probabilities of occurrence of delays 1, 2 and 3 122
Table 6-7 Models with and without time buffers (TB/NTB) 123
Table 6-8 Activities, delays and results of models with and without time buffers 127
Table 6-9 Grouping of models where all work is carried out by the main contractor 129
Table 6-10 Grouping of models where subcontractors are used 132
Table 6-11 P, E, C and median delays of the project 135
Table 6-12 Comparing the estimated delays on activity *Substructure brickwork/blockwork* when carried out by the main contractor and when subcontracted 138

List of figures

Figure 1-1 Flowchart of the study 4
Figure 2-1 Types of channel relationships (adapted from Mentzer *et al* (2001)) 8
Figure 2-2 Perspective on logistics versus SCM (Larson and Halldorsson, 2004) 15
Figure 2-3 Purchase categorization and appropriate buying process (adapted from Rushton *et al.* (2000)) 16
Figure 2-4 The four roles of supply chain management in construction (developed from Vrijhoef and Koskela (2000)) 20
Figure 2-5 Logistics function in construction (Silva and Cardoso, 1999) 21
Figure 2-6 Different types of logistics chains in the construction industry (Wegelius-Lehtonen and Pahkala, 1998) 21
Figure 2-7 Conceptual representation of a make-to-order demand-and-supply chain in residential building (Vrijhoef, 1998) 23
Figure 2-8 Converging construction supply chain versus diverging supply chain (Vrijhoef, 1998) 23
Figure 2-9 Typical supply chain for a make–to-stock manufacturing company and for a project organization (Venkataraman, 2004) 31
Figure 2-10 Dimension of performance measurement system by (Wegelius-Lehtonen, 2001) 36
Figure 3-1 Ways to study a system (Law and Kelton, 2000) 45
Figure 3-2 Steps in a simulation study (Law and Kelton, 2000) 48
Figure 3-3 Research methods adopted 52
Figure 4-1 Sample of *information required schedule* 62
Figure 4-2 Routes of procuring materials of ASC project 66
Figure 4-3 Lead times of procuring materials 66
Figure 4-4 Steps of developing the questionnaire 70
Figure 4-5 Profiles of respondents 73
Figure 5-1 A distribution with minimum, most likely and maximum values for the extent of delays 78
Figure 5-2 The original CPM network with links added 80
Figure 5-3 Delays may occur prior to the start of an activity or during the activity 83
Figure 5-4 Possible positions of delays in the model 85
Figure 5-5 Modelling time buffer (TB) position toward material delivery 86
Figure 5-6 Possible events of two two consecutive delays; i.e. info delay and late delivery of materials with a time buffer 88
Figure 5-7 Probabilistic branches and possible eventualities 89
Figure 5-8 A snapshot of Pertmaster Risk Expert 91
Figure 5-9 Models with relevant delays in detail 94
Figure 5-10 The arrangement of the supply chain delays in optimistic models 96
Figure 5-11 The arrangement of the supply chain delays in pessimistic models 96
Figure 5-12 Trials of number of iterations 99
Figure 6-1 Critical path, criticality index and duration sensitivity of model (1b) O_MC_All (NTB) 110
Figure 6-2 Critical path, criticality index and duration sensitivity of model (11b) SS_All (NTB) 110
Figure 6-3 Distribution of delays on each model 111
Figure 6-4 Distribution of delays on each model in percentage 111
Figure 6-5 Distribution of delays on the critical and non critical paths 114

Figure 6-6 Distribution of delays on the critical and non critical paths shown as percentages 114
Figure 6-7 Examples of typical frequency distributions resulting from various models 115
Figure 6-8 Understanding the graph of frequency distribution of the results of simulations 117
Figure 6-9 Frequency distributions of project durations of models (1) O/P_MC_All (TB/NTB) and (3) O/P_MC_mat (TB/NTB) 119
Figure 6-10 Comparing the frequencies and extent of delays of the project (optimistic vs pessimistic) 119
Figure 6-11 An example of an activity with optimistic and pessimistic delays 121
Figure 6-12 Median delays of optimistic and pessimistic versions with various values of probability of occurrence of delays. 122
Figure 6-13 Comparing histograms of models with and without time buffers 124
Figure 6-14 Frequencies with which the projects finish on time or are delayed 125
Figure 6-15 Extent of delays of projects, with and without time buffers 125
Figure 6-16 Proportion of delays that can be absorbed by the time buffer 127
Figure 6-17 Frequencies with which the projects finish on time or are delayed 130
Figure 6-18 The extent of delays on the project 130
Figure 6-19 Frequencies with which the projects finish on time or are delayed 132
Figure 6-20 Extent of delays of models using subcontractors 133
Figure 6-21 Scatterplots of P, E dan C against median delays 136
Figure 6-22 Estimated versus median delays of simulations 136
Figure 6-23 Comparing delays which are replaced by a subcontractor delay 138
Figure 6-24 Comparing subcontractor delays with delays they are replaced in the models 139

Chapter 1
Introduction

This first chapter provides a fundamental base for this research and is arranged as follows:

1.1 **Background**: This section introduces the importance of this research area.

1.2 **The gap in the research**: This section gives an overview of current research on supply chain management in construction and points out the gap that exists in the literature.

1.3 **Aims and Objectives**: The aims and objectives of the research are described in this section.

1.4 **Scope of the research**: This section explains the limits and the focus of the research.

1.5 **Research arrangement**: This section includes a flowchart that shows diagrammatically the steps taken to complete the work.

1.6 **Structure of the thesis**: This section summarises the content of each chapter in the thesis

1.1 Background

While the construction industry is one of the oldest industries in the world, few would consider it to be an advanced, well-managed and sophisticated industry. Many traditional methods from past decades are still being practised by people working in construction. Recent research has reported that the construction industry is known for its poor performance and low profit margins (Agapiou et al., 1998, Yeo and Ning, 2002, Cox and Ireland, 2002). Many construction processes are ineffective and contain problems regarding delays, budget overruns, quality, controllability, waste, etc (Kornelius and Wamelink, 1998, Vrijhoef and Koskela, 2000, Saad, 1996). Analysis of these problems has shown that a major part of them are associated with supply chains problems (Vrijhoef et al., 1999).

Supply chains in the construction industry can be very complex. Large numbers of subcontractors and suppliers may be involved, especially in a large scale project. In a construction project, any delay of the materials delivery may have knock-on effects on delaying the works and, if they are critical, the project will likely be delayed as a consequence. The same situation will also happen for the late completion of the

subcontractors' works. At a corporate level, the number of parties involved in the supply chain may increase to thousands for the whole year. For example, in 1999, Wates, a family-owned construction company, made payments to more than 3000 suppliers and subcontractors (Scott et al., 2001). This needs special attention of those working in the construction industry to manage their supply chains well so that the best result can be achieved. Therefore, as stated by O'Brien and Fischer (1993), there is an opportunity to make significant improvement in construction supply chain performance.

1.2 The gap in the research

Supply chain management (SCM) was first studied in the manufacturing industry, and this is the reason why most research on SCM is from the perspective of this industry. In the construction industry, the concept is a relatively new concern. Current research related to SCM in a construction context is looking at the issues of: relationships between contractor-subcontractor-supplier (Kadeforsi, 1999, Kale and Arditi, 2001, Greenwood, 2001), subcontractor and supplier selection (Kumaraswamy and Matthews, 2000), organisational perspectives/network alliances in SCM (Love et al., 2002, London, 2001) Just in Time (JIT) practice (Tommelein and Li, 1999, Tommelein and Weissenberger, 1999, Akintoye, 1995), construction processes (Nicolini et al., 2001, Roy et al., 2003), industrial/economic perspective of SCM (London and Kenley, 2001), communication and information technology in SCM (Marsh and Finch, 1999, Edum-Fotwe et al., 2001, O'Brien, 2001), risks in SCM (Tah and Carr, 2001), partnering (Larson, 1995, Bresnen and Marshall, 1999, Briscoe et al., 2001, Packham et al., 2003, Greenwood, 2005), costs (O'Brien, 1997) and the roles of clients in SCM (Briscoe et al., 2004), etc. There has, however, been to date little research on the impact of SCM practice on construction site performance and this opens up an opportunity and provides justification to conduct research on this topic.

1.3 Aims and Objectives

The primary aim of this research is to gain an understanding of the impact of supply chain management practice on construction project performance.

The objectives of this research are:

1. To conduct an in-depth analysis of SCM practice on construction sites.
2. To understand how supply chain management practice impacts on project performance
3. To produce models with various scenarios that simulate the impact of SCM practice on project performance
4. To use the model to test the sensitivity of the project performance to alternative SCM practice

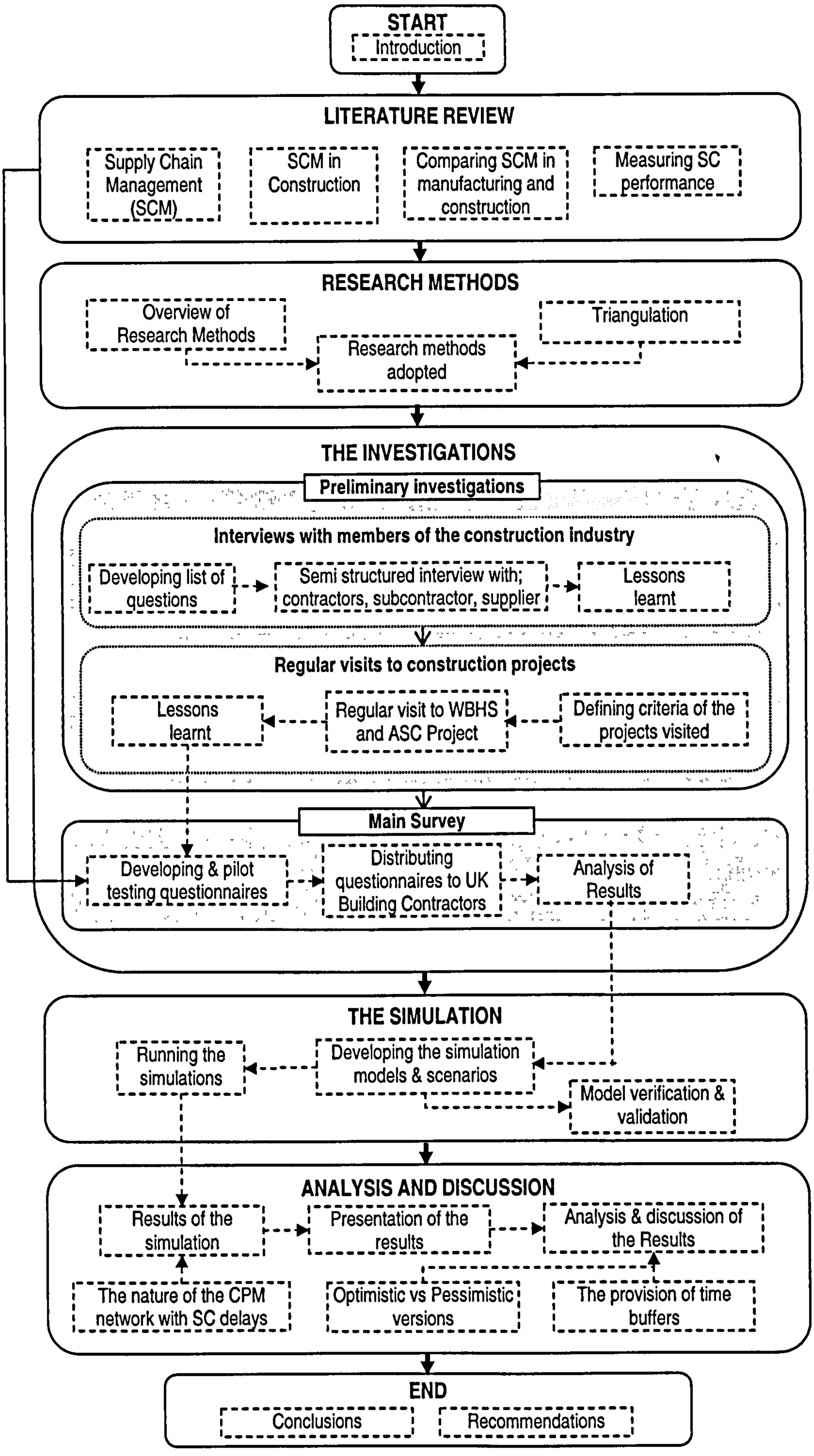
1.4 Scope of the research

The scope of this research is defined as follows:

a. This study focuses on supply chain management practice and project performance at the construction project site level, and not at the organisation level or industry level.
b. Project performance is considered as it relates to *time* only, and not to *cost* or *quality*.
c. The data used for the simulation models were obtained from the main survey within the context of a typical medium-sized building project in the United Kingdom.

1.5 Research Arrangement

Figure 1-1 shows the flowchart for this study. The bold capital title in each thick solid box represents each main task, and detailed activities in each main task are presented inside its box. The arrows linking tasks or activities indicate their relative connections. More detailed information for each task and activity is explained subsequently in the following chapters.


START
Introduction
LITERATURE REVIEW
Supply Chain Management (SCM)
SCM in Construction
Comparing SCM in manufacturing and construction
Measuring SC performance
RESEARCH METHODS
Overview of Research Methods
Triangulation
Research methods adopted
THE INVESTIGATIONS
Preliminary investigations
Interviews with members of the construction industry
Developing list of questions
Semi structured interview with; contractors, subcontractor, supplier
Lessons learnt
Regular visits to construction projects
Lessons learnt
Regular visit to WBHS and ASC Project
Defining criteria of the projects visited
Main Survey
Developing & pilot testing questionnaires
Distributing questionnaires to UK Building Contractors
Analysis of Results
THE SIMULATION
Running the simulations
Developing the simulation models & scenarios
Model verification & validation
ANALYSIS AND DISCUSSION
Results of the simulation
Presentation of the results
Analysis & discussion of the Results
The nature of the CPM network with SC delays
Optimistic vs Pessimistic versions
The provision of time buffers
END
Conclusions
Recommendations

1.6 Structure of the thesis

This thesis is grouped into seven chapters, followed by a list of references and appendices. Each of these chapters is described briefly as follows:

i. Chapter I **Introduction**: The first chapter introduces the background of the research in brief, explains the gap in the research, the aims and objectives, scope of the research, the research arrangement and the structure of the thesis.

ii. Chapter II **Literature Review:** This chapter provides a detailed review of relevant literature on supply chain management in the manufacturing and construction industry, including a comparison of the two, and performance measurement of supply chains.

iii. Chapter III **Research Methods:** This chapter begins by giving an overview of the existing research methods found in the literature. It then continues by defining the research methods adopted, which comprise preliminary investigations, the main survey and the development of simulation models. A discussion on simulation and triangulation is also presented in this chapter.

iv. Chapter IV **The Investigations**: This chapter presents the findings and lessons learnt from the preliminary investigations and the main survey.

v. Chapter V **The Simulation Models**: This chapter describes in detail the process of developing the simulation models, the software used, the various models and scenarios, and model verification and validation.

vi. Chapter VI **Analysis and Discussion of the Results**: Here the results of the simulation are analysed and discussed. It begins by describing the characteristics of the CPM network with the supply chain delays, including the paths through the network, the criticality and sensitivity of the activities, and the distribution of the delays in various models. Analysis and discussion of the results of the various scenarios follow, including the optimistic and pessimistic versions, and models with and without time buffers.

vii. Chapter VII **Conclusions and Recommendations**: The final chapter summarises the main conclusions from this research and proposes recommendations for the industry and for further research.

Chapter 2
Literature Review

This chapter reviews relevant literature on supply chain management. The concept, definitions and scope of supply chain management in manufacturing and in construction are described and compared, including the performance measurement of supply chains in both industries. It consists of four sections, as follows:

2.1 **Supply chain management**: This section describes relevant literature on the basic concepts of supply chain management, its evolution and the development of its bodies of literature. Two related aspects of SCM, i.e. logistics and purchasing are also discussed.

2.2 **Supply chain management in construction**: A comprehensive discussion of supply chain management in the construction industry is provided in this section, including the reasons for wanting to manage supply chains, roles of SCM, logistics, the characteristics of construction supply chains, and stakeholders and problems in construction supply chains.

2.3 **Comparing SCM in manufacturing and construction**: This section compares supply chain management in the manufacturing and construction industry.

2.4 **Measuring supply chain performance**: Literature is included in this section on measuring supply chain performance in the manufacturing and construction industries.

2.1 Supply chain management

2.1.1 Defining the supply chain

In order to develop an understanding of supply chain management, the first thing to know is the definition of a supply chain. A clear definition of supply chains is important as this is the basis to understand further discussions. As with most management concepts, however, there are various definitions of a supply chain proposed by authors, as shown in table 2-1 below.

Table 2-1 Supply chain definitions

Authors	Supply chain definitions
(Lee and Billington, 1992)	"... *a network of facilities that procure raw materials, transform them into intermediate goods and then final products, and deliver the products to customers through a distribution system*"
(La Londe and Masters, 1994)	a set of companies that pass materials forward
(Towill, 1996)	"*a system whose constituent parts include materials supplies, production facilities, distribution services and customers linked via*

Authors	Supply chain definitions
	the feed-forward flow of materials and the feedback flow of information"
(Holmberg, 1997)	"*... a set of organizations performing activities with the purpose of satisfying the ultimate consumer.*"
(Christopher, 1998)	"*The supply chain is the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer*"
(Lambert et al., 1998)	"*.. the alignment of firms that brings products or services to a market*"
(Handfield and Nichols, 1999)	all activities related to the flow and transformation of products from the raw material through the end customer
(Mentzer et al., 2001)	"*... a set of three or more companies directly linked by one or more of the upstream and downstream flows of products, services, finances and information from a source to a customer*"
(Tommelein et al., 2003)	"*a group of companies and individuals working collaborately in a network of interrelated processes*" (as quoted from Arbulu and Ballard (2004))

From the definitions above, it can be concluded that a supply chain involves a set of organisations or a network of firms which are linked together to provide materials, services, information from the source to the ultimate customer.

The definitions above show a general understanding of what a supply chain is. As a further refinement of our understanding of the supply chain definition, Mentzer *et al.* (2001) distinguish different types of supply chains based on the level of the organisations involved as shown in figure 2-1. These are: a basic supply chain, an extended supply chain and an ultimate supply chain.

- *A basic supply chain* consists of a company, an immediate supplier and an immediate customer directly linked by one or more of the upstream and downstream flows of products, services, finances and information.
- *An extended supply chain* includes suppliers of the immediate supplier and customers of the immediate customer which are linked by one or more of the upstream and downstream flows of products, services, finances and information.
- *An ultimate supply chain* includes all the companies involved in all the upstream and downstream flows of products, services, finances and information from the initial supplier to the ultimate customer.

From this categorisation, it can be obviously seen that the supply chain may vary depending on the level and the number of organisations involved. The more the number of the organisations are involved, the more complex the supply chain will be.

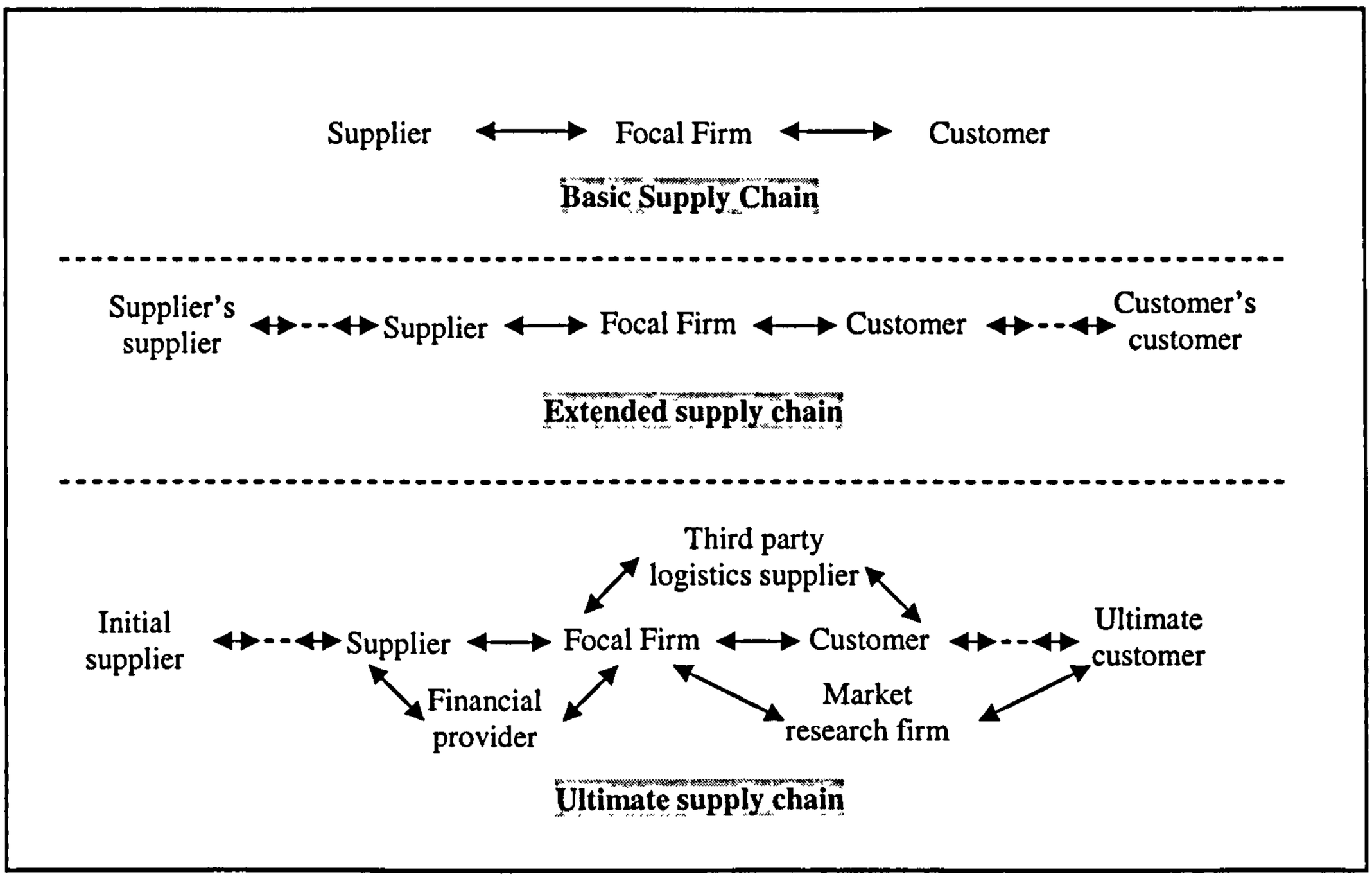


Figure 2-1 Types of channel relationships (adapted from Mentzer *et al* (2001))

2.1.2 Defining supply chain management

As supply chain management has received attention since the early 1980s many researchers have defined it in various ways, which show the different views among researchers of the concept of SCM. As a consequence, there are some overlapping terminologies as well as meanings in the SCM literature (Croom et al., 2000). Tables 2-2 and 2-3 below show some different SCM terminologies and examples of the SCM definitions from many authors. The varieties in using different terminologies and SCM definitions may be caused by the fact that the concept of the SCM has been seen from different points of view in different bodies of literature. (Further discussion of the development of the SCM bodies of literature can be found at section 2.1.4). These varieties may inevitably be the source of confusion and debate (Mentzer et al., 2001, Croom et al., 2000). Yet, a need of pursuing a single universal SCM definition might not be necessary as Saunders (1995) argues that "... *attempts to pursue universal definitions may lead to unnecessary frustration and conflict.*"

Table 2-2 Different SCM labels (developed from Croom *et al.* (2000))

Authors	Different SCM terminologies
Burt (1984)	integrated purchasing strategy
Farmer and van Amstel (1990)	supply pipeline management
Lee and Billington (1992)	value-added chain
Lamming (1993)	buyer-supplier partnership
Nishiguchi (1994)	supply network
Jones (1995)	value stream
New and Ramsay (1995)	lean chain approach
Lewis (1995)	supply base management, strategic supplier alliances
Tan et al. (1998)	supply chain synchronisation
Nassimbeni (1998)	network supply chain
Dyer et al. (1998)	supplier integration

Table 2-3 A sample of definitions of supply chain management (Croom et al., 2000)

Authors	Definitions
Jones and Riley (1985)	An integrative approach to dealing with the planning and control of the materials flow from suppliers to end-users.
Ellram (1991)	A network of firms interacting to deliver product or service to the end customer, linking flows from raw material supply to final delivery.
Christopher (1992)	Network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer.
Lee and Billington (1992)	Networks of manufacturing and distribution sites that procure raw materials, transform them into intermediate and finished products, and distribute the finished products to customers.
Berry et al. (1994)	Supply chain management aims at building trust, exchanging information on market needs, developing new products, and reducing the supplier base to a particular OEM (original equipment manufacturer) so as to release management resources for developing meaningful, long term relationship.
Saunders (1995)	External Chain is the total chain of exchange from original source of raw material, through the various firms involved in extracting and processing raw materials, manufacturing, assembling, distributing and retailing to ultimate end customers.
Kopczak (1997)	The set of entities, including suppliers, logistics services providers, manufacturers, distributors and resellers, through which materials, products and information flow.
Lee and Ng (1997)	A network of entities that starts with the suppliers' supplier and ends with the customers' custom the production and delivery of goods and services.
Tan et al. (1998)	Supply chain management encompasses materials/supply management from the supply of basic raw materials to final product (and possible recycling and re-use). Supply chain management focuses on how firms utilise their suppliers' processes, technology and capability to enhance competitive advantage. It is a management philosophy that extends traditional intra-enterprise activities by bringing trading partners together with the common goal of optimisation and efficiency.

A different perspective in defining SCM has been given by Mentzer *et al.* (2001). They collected definitions of SCM from many authors and classified SCM definitions into three categories; (1) SCM as a management philosophy, (2) SCM as the

implementation of management philosophy and (3) SCM as a set of management processes. Thus, from this point of view, this means that the definition of SCM depends on the way in which the SCM is classified. Table 2-4 below summarises the three categories, including the definitions and characteristics.

Table 2-4 Categorisation of SCM (developed from Mentzer *et al.*(2001))

Categories of SCM	**Definition**	**Characteristics**
As a management philosophy (Ellram & Cooper (1990), Houlihan (1985), Ellram (1990), Jones & Riley (1985), Cooper et al. (1997), Ross (1998), Langley & Holcomb (1992)	*"a set of beliefs that each firm in the supply chain directly and indirectly affects the performance of all the other supply chain members, as well as ultimate, overall channel performance"*	adopts a system approach to viewing the channels as a single entity, rather than as a set of fragmented parts performing individually system approach, and to managing the total flow of goods inventory from the supplier to the ultimate customer, *"a strategic orientation toward cooperative efforts to synchronize and converge intrafirm operational and strategic capabilities into a unified whole,* *a customer to create unique and individualized source of customer value, leading to customer satisfaction"*
As the implementation of management philosophy Cooper & Ellram (1993), Cooper et al. (1997), Ellram & Cooper (1990), Novack et al. (1995)	a set of activities to carry out the philosophy of SCM	*"Integrated behaviour* *Mutually sharing information* *Mutually sharing channel risk and rewards* *Cooperation* *The same goal and the same focus of serving customers* *Integration of processes* *Partners to build and maintain long-term relationship"*
As a set of management processes La Londe (1997), Ross (1998), Cooper et al (1997), Lambert et al (1998)	a process of managing relationships, information and materials flow across organization boundaries in order to meet customer demand	All functions within a supply chain are reorganised as key processes, including customer relationship management, customer service management, demand management, order fulfilment, manufacturing flow management, procurement, and product development and commercialization.

Having reviewed various terminologies and definitions of the SCM, in contrast to Saunders (1995), Mentzer *et al.* (2001) highlight the importance of having a single SCM definition. The purpose of it is that by having a single SCM definition, research and practice of SCM can be improved. Reviewing and pulling together different aspects of SCM, they propose their SCM definition as *"The systemic, strategic coordination of the traditional business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole".*

2.1.3 Evolution of supply chain management

As there are different perspectives on the way of seeing supply chain management, the history of the evolution of supply chain management can also be seen from different perspectives. Rushton *et al.* (2000) describe the evolution of SCM from the perspective of distribution and logistics, as summarized in table 2-5 below.

Table 2-5 The evolution of SCM from the perspective of distribution and logistics (Rushton et al., 2000)

Periods	Description
1950s and early 1960s	Distribution systems were unplanned and unformulated and represented by the haulage industry and manufacturer's own-account fleets. There was little positive control and no real liaison between the various distribution-related functions.
1960s and early 1970s	The concept of physical distribution was developed gradually with recognition that physical activities such as transport, storage, materials handling and packaging could be linked together and managed more efficiently. These enabled the use of system approach function and total cost perspective.
1970s	The important decade in the development of the distribution concept. The need to include distribution in the functional management organization was recognized. There was a change in the structure and control of distribution change, a decline in the power of the manufacturers and suppliers and an increase in that of the major retailers. Large retails chains developed their own distribution structures to supply their stores,
1980s	Professionalism within distribution increased significantly with a move towards the longer term planning and attempts to identify and pursue cost-saving measures, including centralized distribution, severe reduction in stock holding and the use of computer to provide information and control. The growth of third party distribution service was significance. The concept of and the need for integrated logistics systems were recognized.
Late 1980s and early 1990s	As information technology emerged, organizations began to broaden their perspectives in terms of functions that could be integrated. This covered the combining of materials management with physical distribution (the inbound side vs the outbound side) which led to the improvement of customer service and reduce the associated costs.
1990s	The process was developed further to encompass functions that contribute to the provision of a product to a final customer across the boundary of organisation, which is also know as *supply chain management.* There was a recognition of the involvement of different organisations in getting a product to a market place.
2000 and beyond	The competition among firms is increasing which has led the idea of redefining business goals and reengineering of entire systems, including logistics. Logistics is seen as a key enabler for business improvement which has a positive value added, and no longer seen as a cost burden.

The evolution of SCM from another perspective is given by Tan (2001). He describes the evolution of supply chain management from the perspective of management of production as summarized in table 2-6 below.

Table 2-6 Evolution of SCM from the perspective of management of production (Tan, 2001)

Periods	Description
1950s and 1960s	Most manufacturers emphasized on mass production strategy with little product or process flexibility in order to reduce the unit production cost which led to slow down the development of new products and the limitation of technology and capacity. 'Bottleneck' operations arose with inventory to maintain a balanced line flow. Consequently, firms had a huge investment in work in process (WIP) inventory. Most manufacturers considered it too risky to share technology and expertise with customers or suppliers, so they ignored the importance of cooperative and strategic buyer-supplier partnership. Purchasing function was not much involved, since managers thought it was a service to production.
1970s	The concept of Manufacturing Resource Planning was introduced that made the managers realized the impact of huge Work in Process (WIP) on manufacturing cost, quality, new product development and delivery lead-time. Manufacturers adopted a new materials management concept to improve performance within the company.
1980s	World-class organizations had to improve design flexibility to offer low cost, high quality and reliable products due to the intense global competition in this period. Manufacturers had begun focusing on manufacturing efficiency and cycle time by utilizing just-in-time (JIT) and other management initiatives. They began to realize the potential benefit and importance of strategic and cooperative buyer-supplier relationship. *The concept of supply chain management emerged as manufacturers experimented with strategic partnerships with their immediate suppliers.* Experts in transportation and logistics considered that in materials management, there should be an integration between physical distribution and transportation functions as an integrated logistics concept, also known as supply chain management.
1990s	Organizations extended best practice in managing corporate resources to include strategic suppliers and the logistics function in the value chain. Cost and quality consideration was emphasized more in supplier efficiency. Manufacturers bought products only from certified suppliers in order to avoid duplicating non-value-adding activities such as inspection. More recently, many manufacturers and retailers adopt the concept of supply chain management to improve efficiency across the value chain. They involve their suppliers in new product development. Retailers also integrate their physical distribution function with transportation partners for direct store delivery without any necessary inspection.

Regarding the multi perspectives of SCM evolution, Croom *et al* (2000) state *"Such a multidisciplinary origin and evolution is reflected in the lack of robust conceptual frameworks for the development of theory on supply chain management. As a consequence the schemes of interpretation of supply chain management are mostly partial or anecdotal with a relatively poor supply of empirically validated models explaining the scope and form of supply chain management, its costs and its benefits".*

The different perspectives on the way of seeing the SCM evolution has inevitably influenced the development of the SCM concept and bodies of literature. During its development, SCM bodies of literature have received many contributions from other fields. This will be described further in the next section.

2.1.4 Development of supply chain management bodies of literature

Croom *et al.* (2000) argue that "*The origins of the concept of supply chain management are unclear, but its development was initially along the lines of physical distribution and transport, using the techniques of industrial dynamics*". They highlight different subject literatures which have contributed to SCM in different perspectives, i.e. purchasing and supply chain literature, logistics and transport literature, marketing literature, organisational behaviour, industrial organisation, transaction cost economics and contract review literature, contingency theory, institutional sociology, system engineering literature, network literature, best practice literature, strategic management literature, and economic development literature. Table 2-7 below shows the particular concerns of six of these areas as they relate to the field of supply chain management.

Table 2-7 Principal component bodies of supply chain literature (Croom et al., 2000)

Strategic management	*Relationships/partnerships*
Strategic Networks	Relationships Development
Control in the supply chain	Supplier Development
Time-Based Strategy	Strategic Supplier Selection
Strategic Sourcing	Vertical Disintegration
Vertical Disintegration	Partnership Sourcing
Make or Buy decisions	Supplier Involvement
Core Competencies focus	Supply/Distribution Base Integration
Supply Network Design	Supplier Assessment (ISO)
Strategic Alliances	Guest Engineering Concept
Strategic Supplier Segmentation	Design for Manufacture
World Class Manufacturing	Mergers Acquisitions, Joint Ventures
Strategic Supplier Selection	Strategic Alliances
Global Strategy	Contract View, Trust, Commitment
Capability Development	Partnership Performances
Strategic Purchasing	Relationship Marketing
Logistics	*Best practices*
Integration of materials and information flows	JIT, MRP, MRP II
JIT, MRP, Waste Removal, VMI	Continuous Improvement
Physical Distribution	Tiered Supplier Partnerships
Cross Docking	Supplier Associations (kyoryoku kai)
Logistics Postponement	Leverage Learning Network
Capacity Planning	Quick Response, Time Compression
Forecast Information Management	Process Mapping, Waste Removal
Distribution Channel Management	Physically efficient Vs. Market Oriented Supply
Planning and Control of Materials Flow	Chains
Marketing	*Organisational behaviour*
Relationship Marketing	Communication
Internet Supply Chains	Human Resources Management
Customer Service Management	Employees' Relationships
Efficient Consumer Response	Organisational Structure
Efficient Replenishment	Power in relationships
After Sales Service	Organisational Culture
	Organisational Learning
	Technology Transfer
	Knowledge Transfer

As can be seen in table 2-7 above, there are some partial overlaps among the subject areas. For instance, *relationship marketing* is an overlap between *marketing* and *relationship/partnership*, and *JIT* and *MRP* overlap between *logistics* and *best practices*. These overlaps show that in fact a particular topic can be seen from more than one subject area with different perspectives. In short, all these have contributed and enriched the SCM as a field of study.

Although the overlaps may enrich the supply chain management as a field of study, they might also blur the boundaries of SCM. Larson and Halldorsson (2004) argue

that *"The unclear conceptual boundaries of SCM make it difficult to design educational and research programmes in SCM without large overlap with other fields such as logistics, marketing, operations management and purchasing"*. In order to give a better picture of other fields related to SCM, e.g. logistics and purchasing, the next section describes them in more detail.

2.1.5 SCM, logistics and purchasing

Supply chain management is a large area, as indicated by the development of its bodies of literature which consists of many different fields from which some overlaps can be found. Among these fields, logistics and purchasing have been chosen to be described in more detail in the next section, since they are closely related to SCM as well as often causing some confusion and debate.

2.1.5.1 Logistics

Logistics has been defined in many ways. The Concise Oxford Dictionary (1995) defines logistics as *"the organization of moving, lodging, and supplying troops and equipment."* This definition indicates that the term logistics initially emerged from military practice.

The Council of Logistics Management (CLM) (2004) states that logistics management is "*that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements*". Quayle and Jones (1999) argue that logistics is *"the process which seeks to provide for the management and co-ordination of all activities within the supply chain from sourcing and acquisition, trough production where appropriate and through distribution channels to the customer."* From these definitions, logistics can be seen as a part of SCM.

As a matter of fact, seeing logistics as part of SCM is not the only view. Some other authors have different views of logistics in relation to SCM. The link between logistics and SCM is explained briefly in the next section below.

2.1.5.2 Logistics and SCM

There is a confusion and lack of agreement about the definition and relationship between logistics and supply chain management. In relation to this, Larson and Halldorsson (2004) propose four different perspectives of supply chain management in relation to logistics. The four perspectives are traditionalist, relabeling, unionist and intersectionist (figure 2-2).

The traditionalists consider supply chain management is just a small part of logistics. The relabeling perspective simply gives a new name to logistics and now it is called supply chain management. Unionists reverse the traditionalist view and consider that logistics is just a part of supply chain management, with other functions like marketing, operations management, purchasing, etc are also being included in SCM.

The intersectionists see logistics and SCM as separate entities, but with areas of overlap.

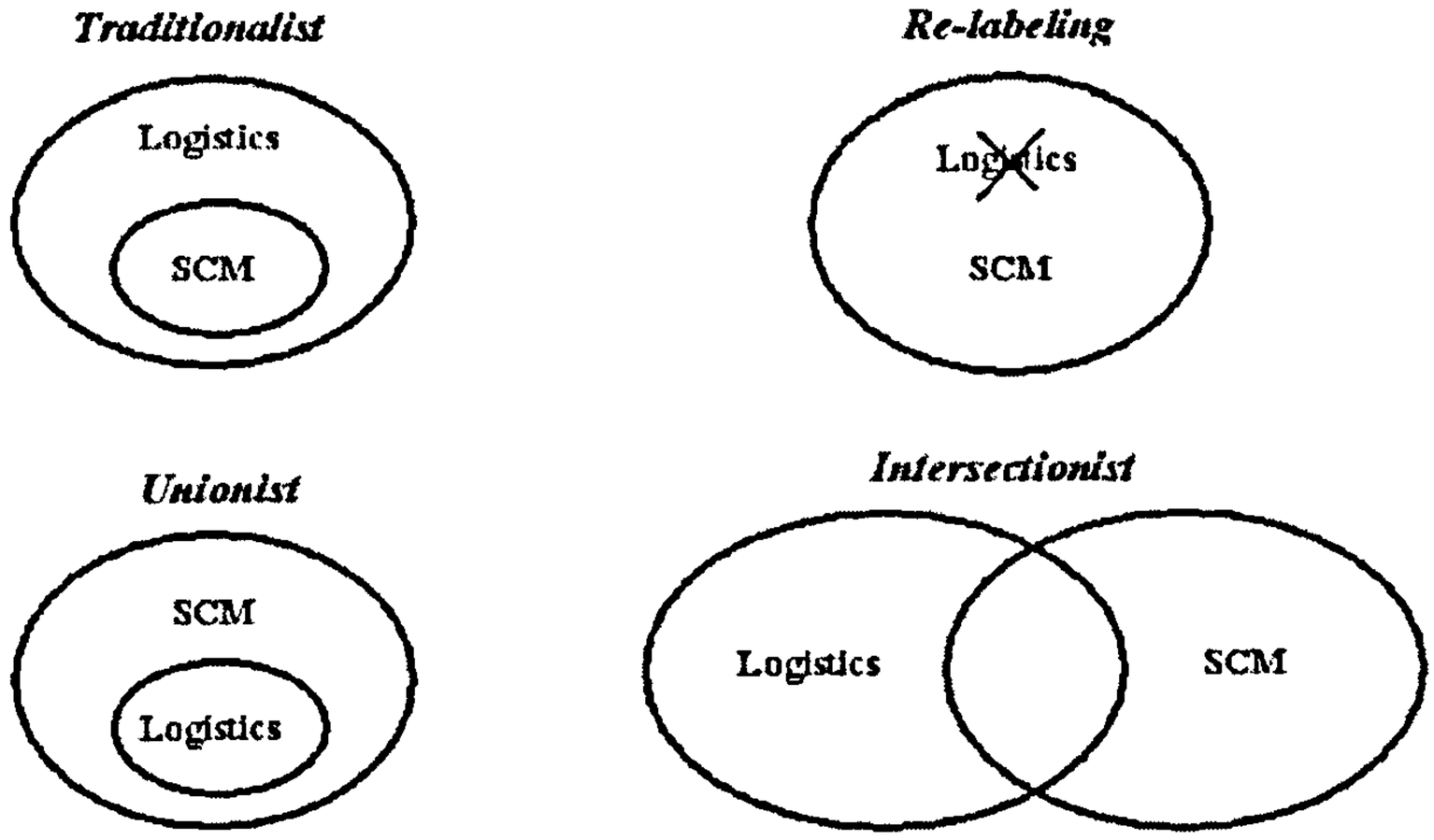


Figure 2-2 Perspective on logistics versus SCM (Larson and Halldorsson, 2004)

In this research, the unionists view is adopted. This view refers to The Council of Logistics Management (CLM) (2004) which defines logistics as part of supply chain management. This means that logistics, like other functions (marketing, operation management, purchasing, etc) is considered as part of SCM. Purchasing will be discussed in more detail in the next section.

2.1.5.3 Purchasing

Purchasing can be defined as the process of buying whose function involves obtaining the right material, in the right quantities with the right delivery from the right source and at the right price (Arnold, 1991).

Rushton *et al.* (2000) suggest that purchases can be categorized based on the hierarchy of importance, as shown in figure 2-3 below. The reason for this segmentation is to ensure that the appropriate amount of time and effort are spent on the purchases that matter most to the organisation. Products need to be classified according to their criticality to the business and the value of annual purchases. Based on the hierarchy of importance and the annual purchase value, purchases can be segmented into four categories, i.e. routine purchases, commodities, critical items and strategic items. At the one end, a routine purchases is one that has a low annual purchase value and is not critical to the business. At the other end, a strategic item is one that is both very critical to the business and has a high annual purchase value.

This kind of categorisation, i.e. criticality to the business vs annual purchase value, can then be followed by another categorisation based on the buying process of the products. Routine purchases can be made quickly and easily through on-line

catalogues which speed up the process and limit the cost of transactions. A tendering process is appropriate for high annual purchase value commodities to obtain the best price. For critical items, which have low annual purchase value, a network of approved suppliers and a formal system for approving suppliers are most appropriate. For strategic items, which have high annual purchase value and are very critical to the business, a strategic partnership is the most appropriate.

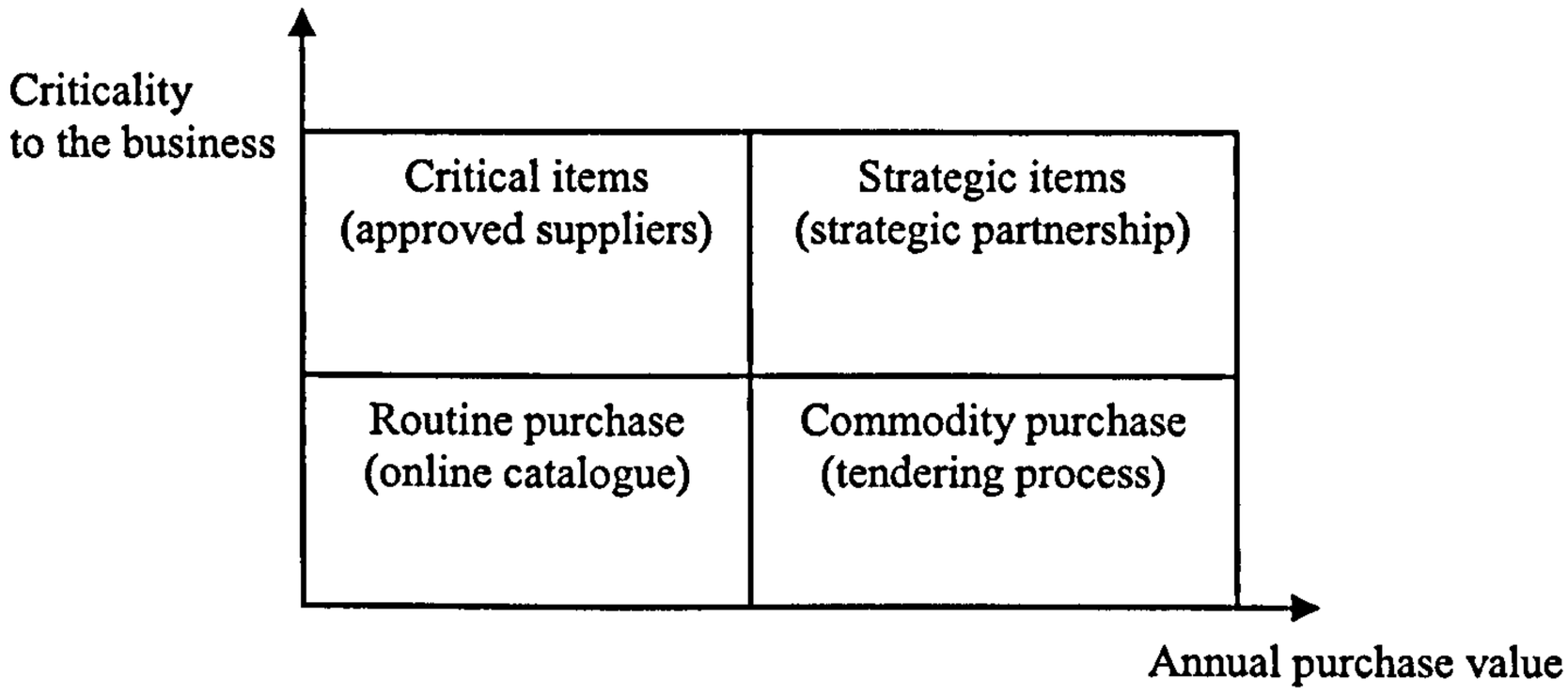


Figure 2-3 Purchase categorization and appropriate buying process (adapted from Rushton *et al.* (2000))

2.2 Supply chain management in construction

It should be noted that the nature of the construction industry is different in many ways from the manufacturing industry, from which many of the SCM concepts were originally developed. For example, the construction industry is characterised as project-based with temporary organisations while manufacturing industry is more likely to have continuous production with a more permanent organisation. (More detailed discussion of the different natures of the construction and manufacturing industry can be found in section 2.3). Cox et al. (2006) complain that many academic writers and practitioners in the construction industry simply copy the ideas of supply chain partnering from Japanese and Western automotive industry. They argue that much of the thinking is simplistic and fails to understand the nature of construction supply chains. In order to cope with this different nature, it is necessary to position the framework of SCM in the context of the construction industry. Modifications will be needed to establish the concepts of SCM in the construction industry and to suit the context.

Few researchers in the construction industry have defined their own SCM definitions, as shown in table 2-8. This can be understood as an effort to define the limitation of SCM to suit the construction industry context which might be different from the manufacturing industry. For example, an extraordinary effort to sum up the SCM definitions has been carried out by Vrijhoef (1998) who captured 35 definitions from many authors, some of which are shown in table 2-9. He distinguishes some commonalities among them, i.e.;

- *"embracing an integral perspective across the supply chain*
- *enhancing customer responsiveness*
- *adopting flow management of materials and information*
- *optimal co-ordination and configuration of the supply chain process*
- *supply chain analysis and improvement, including the reduction of inventory and costs*
- *rejection of intra and inter-organisational boundaries*
- *achieving partnership arrangements*"

He then proposes his own definition of SCM as *'the establishment, co-ordination and maintenance of an optimised supply chain that operates effectively, fulfilling all its preconditions and goals optimally, and involving all its stakeholders'.*

Table 2-8 SCM definition in construction supply chain research

SCM definition in construction	Author(s)
"Supply chain management is the system of suppliers and contractors producing, delivering, and installing materials for construction projects."	(O'Brien and Fischer, 1993)
'the establishment, co-ordination and maintenance of an optimised supply chain that operates effectively, fulfilling all its preconditions and goals optimally, and involving all its stakeholders'	(Vrijhoef, 1998)
"Construction supply chains are networks of interrelated processes designed to satisfy end customer needs".	(Arbulu and Tommelein, 2002b)
"Supply chain management is the management of all the processes that are required to deliver a service or a product for a customer through a network of organizations with minimum waste and maximum value".	(Elfving, 2003)
"The practice of a group of companies and individuals working collaboratively in a network of interrelated processes structured to best satisfy end customer needs while rewarding all members of the chain".	(Tommelein et al., 2003)

A most straight forward definition is proposed by O'Brien and Fischer (1993) who state "*supply chain management is the system of suppliers and contractors producing, delivering, and installing materials for construction projects.*" For this research, this definition is adopted with some refinement as follows; "*supply chain management is the system where suppliers, contractors and client/architect work together under the coordination of the main contractor to produce, deliver, install and utilise information, materials, plant, temporary work, equipment and labour and other resources for construction projects.*"

Table 2-9 The list of definitions of supply chain management (Vrijhoef, 1998)

Definition	**Author(s)**
'Supply chain management deals with the total flow of materials from suppliers through end users.'	Jones et al. (1985)
'Supply chain management covers the flow of goods from supplier through manufacturer and distributor to the end user.'	Houlihan (1988)
'Control the flow of material from suppliers, through the value adding (production) processes and distribution channels, to customers.'	Stevens (1990)
'(...) an integrative philosophy to manage the total flow of a distribution channel from the supplier to the ultimate user.'	Ellram et al. (1990)
'Supply chain management is simply a different way of competing in the market.'	Ellram (1991)
'Supply chain management is an innovative form of competition which has grown out of, and is supported by, the current economic environment. Supply chain management represents a tremendous opportunity for firms to utilise assets, particularly	Ellram (1991)

Definition	Author(s)
inventory, more effectively, while decreasing the ownership and management risks of vertical integration.'	
'Supply chain management is defined as an integrative approach to dealing with the planning and control of the materials flow from suppliers to end-users.'	Ellram (1991)
'Supply chain management really represents a network of firms interacting to deliver a product and service to the end customer, linking flows from raw material supply to final delivery.'	Ellram (1991)
'Supply chain management is an integrative approach to using information to manage inventory throughout the channel, from source of supply to end-user.'	Ellram (1991)
'Supply chain management covers the flow of goods from the supplier through the manufacturer and distributor to the end user.'	Novack et al. (1991)
'(...) supply chain management is used to refer to the chain linking each element of the production and supply process from raw materials through to the end customer.'	Scott et al. (1991)
'The supply chain concept consists of actively managed channels of procurement and distribution. It is the group of firms that add value along product flow from original raw materials to final customers. It concentrates on relational factors rather than transactional ones.'	Cavinato (1992)
'Supply chain management covers the flow of goods from supplier through manufacturing and distribution chains to the end user.'	Christopher (1992)
'Supply chain integration is only a natural result of redesigned business processes not realignment of existing functional organisations.'	Hewitt (1992)
'Networks of manufacturing and distribution sites that procure raw materials, transform them into intermediate and finished products, and distribute the finished products to customers.'	Lee et al. (1992)
'Supply chain management is viewed as lying between fully-vertically-integrated systems and those where each channel member operates completely independently'.	Cooper et al. (1993a)
'Supply chain management is an approach whereby the entire network from which suppliers through the ultimate customer, is analysed and managed in order to achieve the "best" outcome for the whole system.'	Cooper et al. (1993a)
'(...) approach (that) will enable a manufacturing operation to better manage its supply chain, ultimately improving customer satisfaction levels while reducing overall costs.'	Davis (1993)
'(...) a networking approach to value chain optimisation.'	Lamming (1993)
'(...) moving from an adversarial form of contracting to higher trust obligational relationships.'	Morris et al. (1993)
'(...) technique that looks at all the links in the chain from raw materials suppliers through various levels of manufacturing to warehousing and distribution to the final customer.'	Turner (1993)
'Supply chain management is really an operations approach to procurement. It requires all participants of the supply chain to be properly informed. With supply chain management, the linkage and information flow between various members of the supply chain are critical to overall performance.'	Johannson (1994)

2.2.1 Why do we need to manage supply chains in construction?

Some studies in the manufacturing industry have shown that companies that manage their supply chains have reduced their inventory level significantly, increased inventory turnover rate, reduced supply cost, increased productivity, sales and profit (Venkataraman, 2004). He argues that there are three reasons why we need to manage supply chain. First, the competition in the market is getting intense with not only regional, but also national and international players. Second, inventory is a non-value-adding asset and costs significantly to the business, therefore effective supply chain management solution is needed. Third, the supply chain is becoming very complex which increases the risks, e.g. inaccurate forecast, late deliveries, etc.

In the context of construction, Vrijhoef (1998) argues that *"The benefits of supply chain management are quite obvious. It provides improvement opportunities for virtually all problematic issues. [...] provides strong themes to enhance the cohesion and controllability of construction supply chains as a whole. [...]help optimising the material and information flows in construction supply chains by means of measurement, redesign and reengineering of the chain process. [...] brings up possibilities to enhance operations, logistics and materials management, and intensify collaboration and communication across the supply chain".*

The evidence from a recent study (Greenwood, 2004) suggests that managing construction supply chains through partnering has dramatic effects in the areas of *cost* and *cost predictability* (Greenwood, 2005). The partnering reported in this paper, resulted in a saving of 31% on the accepted tender price for aluminium windows. It was also pointed out that more than 70% of a project's costs are associated with the

supply chain (suppliers and subcontractors) rather than with the main contractor. This means that managing the supply chain effectively opens up an opportunity for significant reduction in the project's costs. This argument supports Edum-Fotwe *et al.* (1999) who said that competition within the construction industry in the next decade or two will be between supply chains, and not among individual companies

While in the manufacturing industry the supply chain management concept is widely understood, in the construction industry it is still a relatively new concept (Arbulu and Ballard, 2004). Some efforts have been made to widen the understanding of construction supply chains, as Arbulu and Ballard (2004) state that people in construction, i.e. clients, contractors, suppliers and subcontractors, are still exploring what SCM is, how it works to increase competitive advantage and what are its dynamics. A very useful contribution to the roles and how SCM works in the construction industry has been proposed by Vrijhoef and Koskela (2000) as described in the next section.

2.2.2 Roles of SCM in Construction

Vrijhoef and Koskela (2000) introduced four major roles for supply chain management in construction, which may be seen from the perspective of the supply chain itself, the construction site, or both. The roles are not mutually exclusive but often used jointly.

First, the focus may be on the impacts of the supply chain on site activities, with the goal of reducing costs and durations of site activities. The main concern is to ensure the flow of materials and labour to the site to avoid disruption to the workflow. The main contractor is in the best position to adopt this focus. Second, the focus is on the supply chain itself. The goal is to reduce the costs related to logistics, lead time and inventory. Material and component suppliers may adopt this focus. Third, the focus may be on transferring activities from the site to earlier stages of the supply chain. The goal is to reduce the total costs and duration. This focus may be initiated by suppliers or contractors. Fourth, the focus may be on the integrated management and improvement of the supply chain and the site production, where site production is subsumed into SCM. This focus may be initiated by clients, suppliers or contractors. Figure 2-4 summarises the four roles of supply chain management in construction.

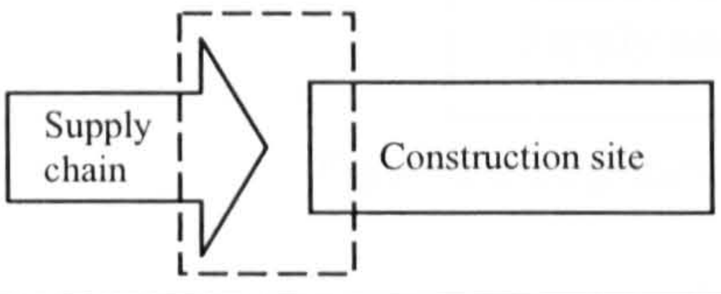
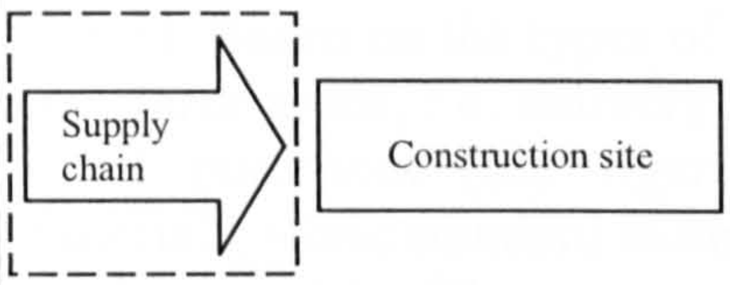
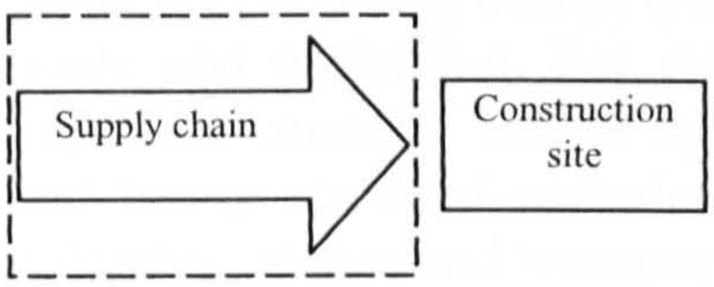
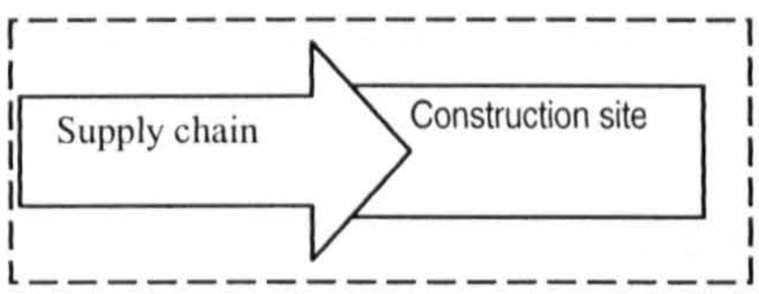
Roles	Focus	Goals	Who may adopt/initiate this focus?
1 	the impacts of the supply chain on site activities	To reduce costs and duration of site activities	The contractor
2 	the supply chain itself	Reducing costs related to logistics, lead time and inventory	Material and component suppliers
3 	transferring activities from the site to earlier stages of the supply chain	To reduce total costs and durations	Suppliers or Contractors
4 	the integrated management and improvement of the supply chain and the site production	Site production is subsumed into SCM	Clients, suppliers or subcontractors

Figure 2-4 The four roles of supply chain management in construction (developed from Vrijhoef and Koskela (2000))

In dealing with SCM practice on a construction site, logistics, as a subset of SCM, plays an important role in managing materials as well as information on a construction site. The scope of logistics and how logistics applies in the context of construction are explained further below.

2.2.3 Logistics in construction

Silva and Cardoso (1999) argue that logistics in construction may be understood as a multidisciplinary process that involves materials supply, storage, processing and handling, manpower supply, schedule control, site infrastructure and equipment location, site physical flow management and management of information related to all physical and services flows. All these activities are carried out before and during construction works. In a construction firm, the logistics functions can be divided into supply logistics and site logistics (figure 2-5). Supply logistics are related to activities in the production process, e.g. supply resources (materials, equipment and manpower) specification, supply planning, acquisition of resources, transport to site and delivery, and storage control. Site logistics are more related to the physical flow planning, organizing, directing and controlling of activities on site; e.g. management of handling systems, safety equipment, site layout, definition of activity sequence etc.

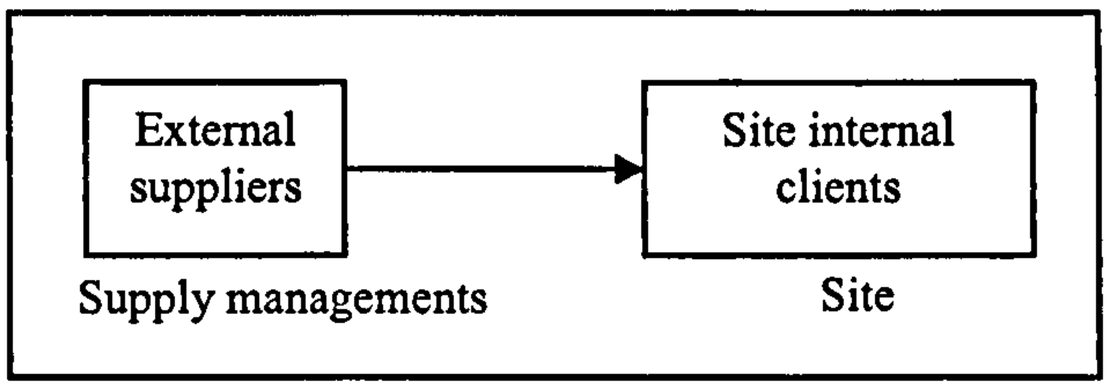


Figure 2-5 Logistics function in construction (Silva and Cardoso, 1999)

A different view on logistics has been proposed by Wegelius-Lehtonen and Pahkala (1998). Based on the types of material, they classify the delivery process of materials into three types, i.e. delivery chains of customized materials, standard materials and small purchases (see figure 2-6). Customized materials are designed-to-order materials, while standard materials and small purchases are make-to-order or make-to-stock materials. They argue that the delivery process of these three have typical problems regarding design changes, timing, shortages, handling and storing, damages, waste and packaging. For standard materials, the material flows become the most important concern. This is due to the difficulty in handling and storing typical bulky and heavy standard materials at the construction site. Thus, careful planning of unloading places and transportation at the site is needed in advance. By contrast, for customized materials, information flows are the most important concern. Failure in obtaining the required information may result in the disruption of the project.

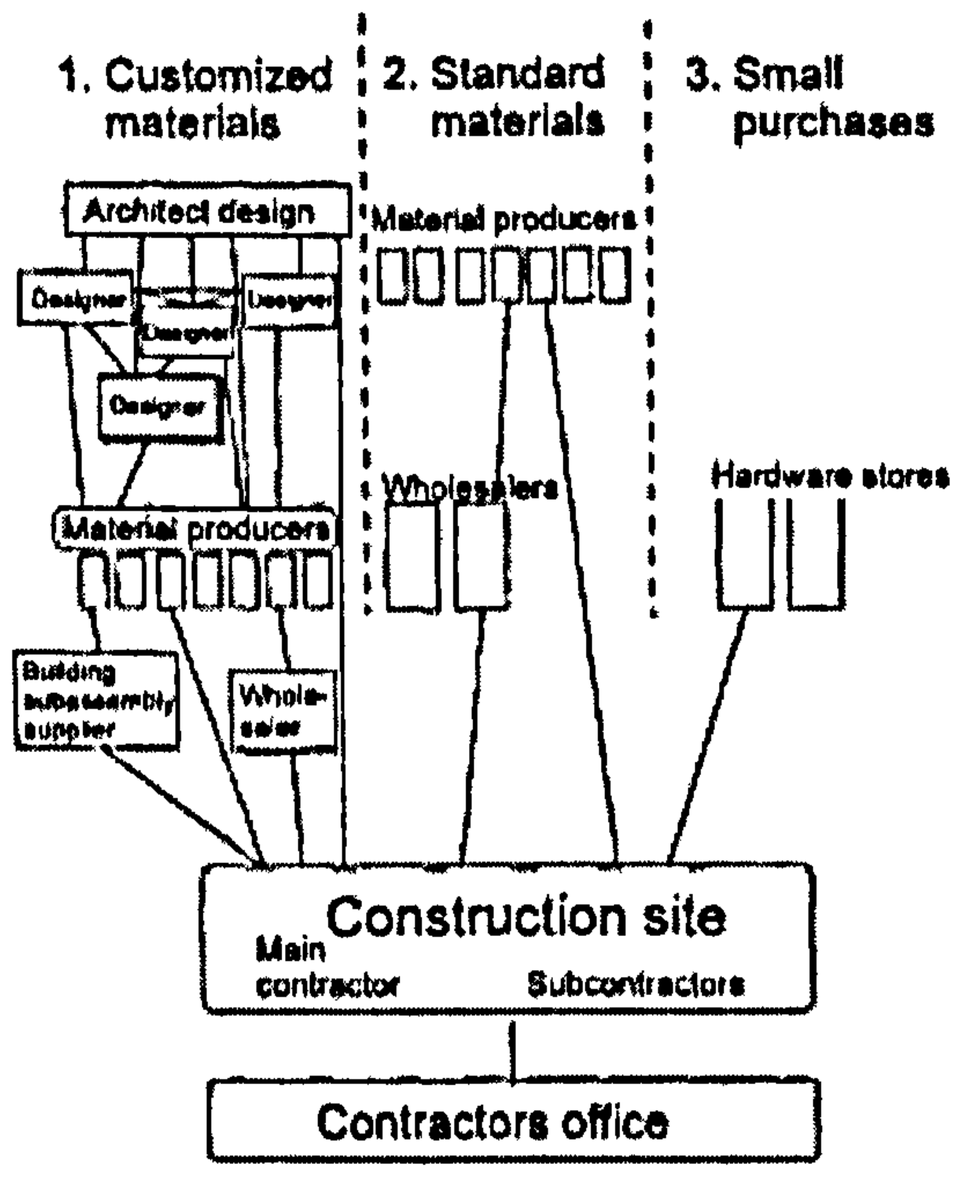


Figure 2-6 Different types of logistics chains in the construction industry (Wegelius-Lehtonen and Pahkala, 1998)

In line with the logistics definition from the Council of Logistics Management (CLM) (2004), logistics in this case has been seen as part of supply chain management. Just as supply chain management needs adjustment to suit the context of the construction

industry, the logistics function also needs it. To have a better understanding of the context, it is necessary to understand the characteristics of construction supply chains in more detail.

2.2.4 Characteristic of construction supply chains

One obvious characteristic of construction supply chains is that construction supply chains can be very complex, especially in large building projects. The complexity maybe due to the number of different materials needed on site and also the number of parties (i.e. suppliers and subcontractors) involved in the project. The complexity may increase as the suppliers are supplied by their suppliers, and the subcontractors are dealing with their suppliers and subcontractors which may possibly subcontract their works, partly or wholly, to other subcontractors. In general, the larger the scope of the project, the more complex the supply chain will be. From the perspective of a construction company, the complexity of the supply chain is also obvious. For a whole year, a construction company may deal with hundreds or thousands of suppliers and subcontractors for its projects. For example, in 1999, Wates, a family-owned construction company, made payments to more than 3000 suppliers and subcontractors (Scott et al., 2001).

Other specific characteristics of construction supply chains have been identified by Vrijhoef (1998). From his research on residential building, he confirms that construction supply chains are typically make-to-order, converging, temporary and fragmented, as described below:

1. Make-to-order supply chain

Traditionally, it is very often the end user who takes the initiative to start a construction project and that is why most construction project is customer driven. The production process of a construction project starts and ends with the end user. Figure 2-7 below conceptualizes the traditional construction process in residential building. It should be noted that there has been a modernisation of contractual and ownership arrangements between parties in the construction process in the last few decades, although it is argued that the operational arrangements have not changed much.

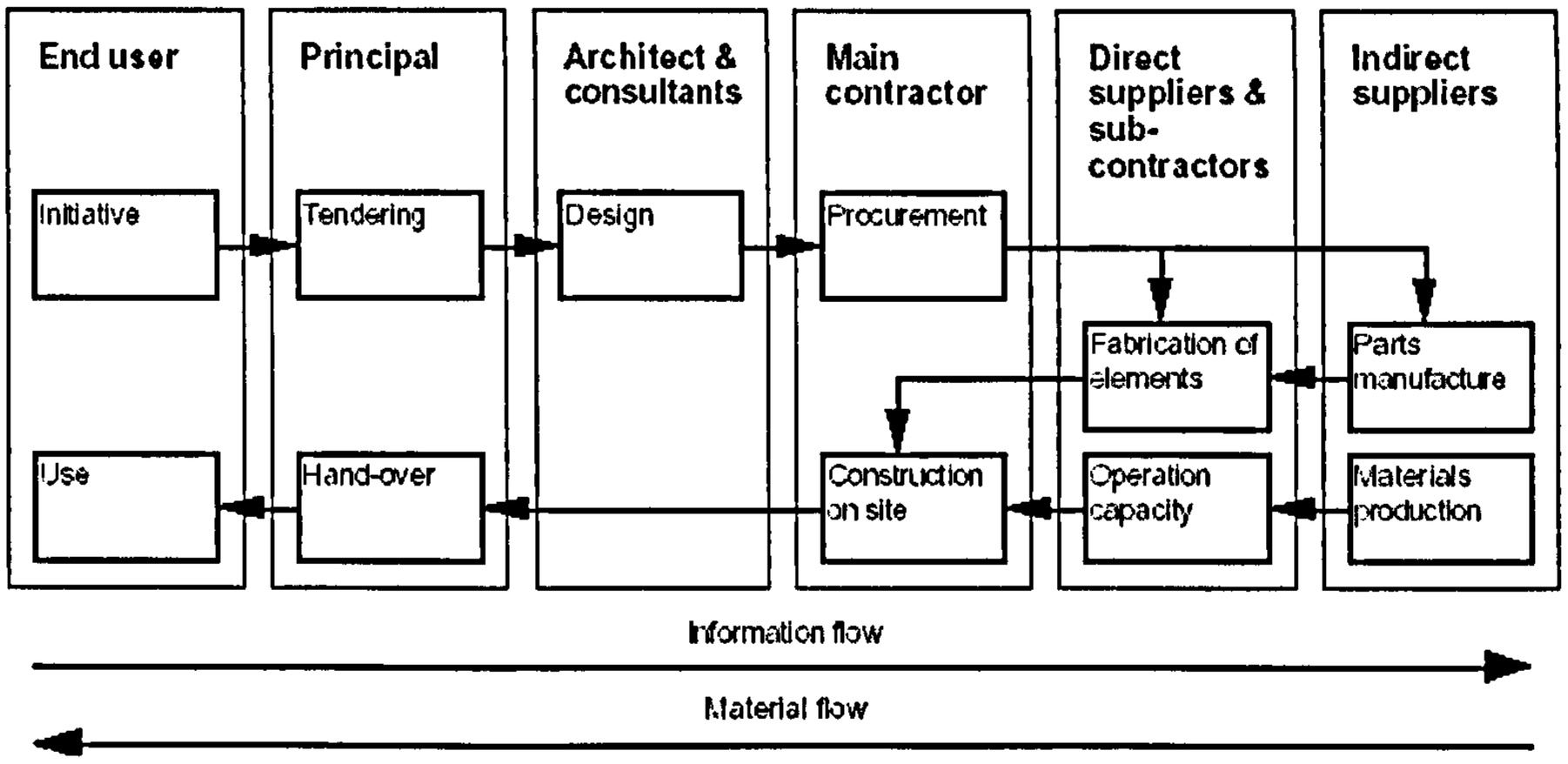


Figure 2-7 Conceptual representation of a make-to-order demand-and-supply chain in residential building (Vrijhoef, 1998)

2. Converging supply chain

In construction projects, it is normal for materials, documents, operation capacity and so on to be delivered and assembled on site by suppliers and subcontractors under the supervision of the main contractor. The end user will usually only be one or a limited member of people. So, the construction supply chain is likely to be converging – quite the opposite of the manufacturing supply chain (figure 2-8).

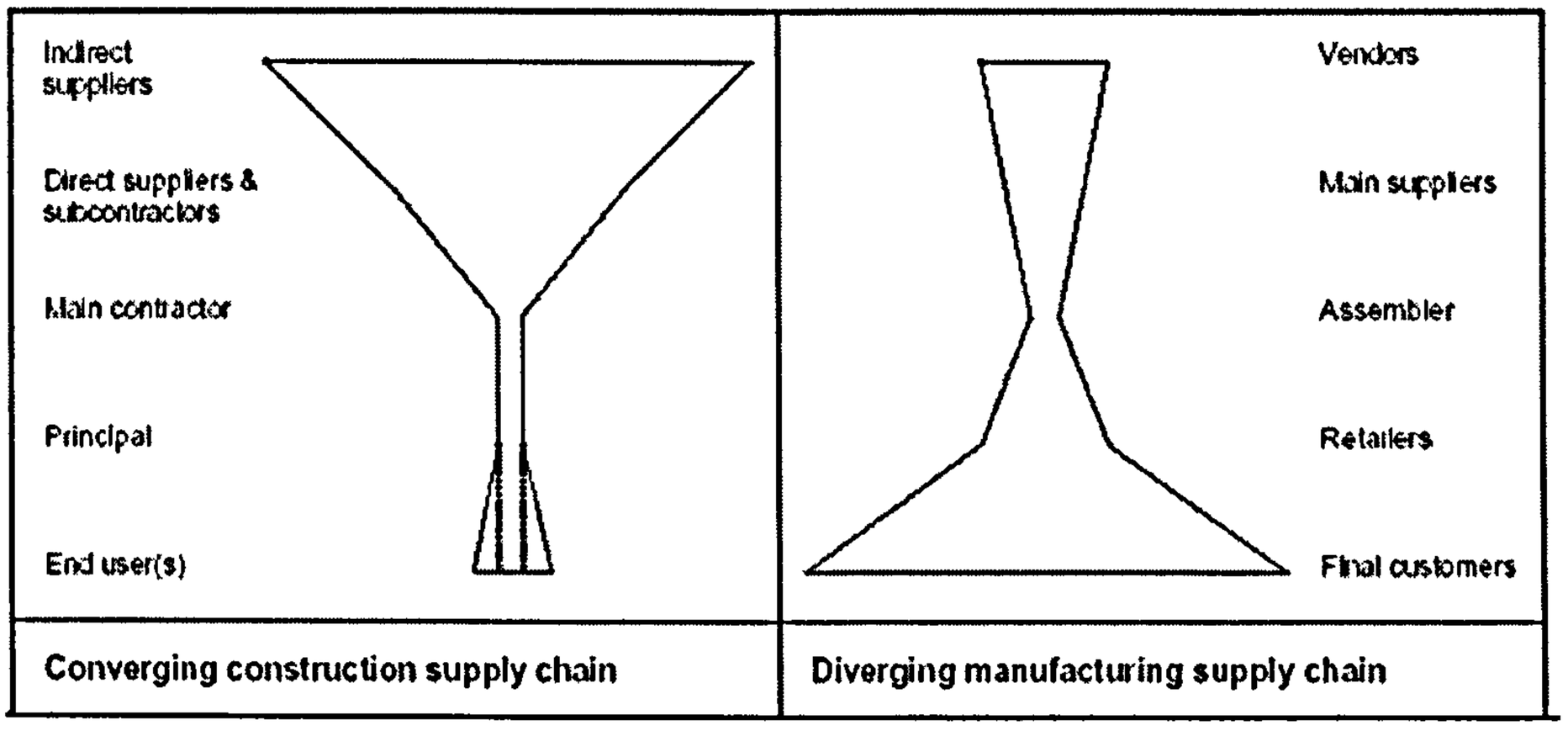


Figure 2-8 Converging construction supply chain versus diverging supply chain (Vrijhoef, 1998)

3. Temporary supply chain

The nature of construction is project-based. This means that when the project is complete, the organisations involved are normally dismissed. The organizations involved in the project have to end their roles as a consequence. This short term coalition, with frequent changing members may result in a fluctuation of productivity.

4. Fragmented supply chain

   Fragmentation in the construction process is one of the important characteristics of construction. Many participants are active in the different stages of the construction process, and the distribution of authority and responsibility changes often during the process. Fragmentation causes difficulties in collecting data, solving problems, developing new methods or taking appropriate action.

Another characteristic of construction supply chains is highlighted by Muya *et al.* (1999). He points out that there are three types of construction supply chain, as follows:

1. The primary supply chain, which delivers the materials that are incorporated into the final construction product, for example, raw materials, components, sub assemblies and mechanical and electrical equipment.
2. The support chain, which provides equipment, expertise and materials that facilitate construction, for example falsework and framework, excavation supports, scaffolding, temporary works related to operation of equipment, site access.
3. The human resource supply chain, which involves the supply of labour and the supervisory staff as inputs to the construction process.

Given the fact that the characteristics of the construction industry are different form others (e.g. manufacturing industry), this will inevitably distinguish the construction supply chains from others, as has been previously described. To sum up, the construction supply chain can be classified as the primary chain, the support chain and the human resource supply chain, and be characterized as complex, make-to-order, converging and temporary supply chains.

People or organisations which are involved in the construction industry may have significant contributions to the characteristics of construction supply chains. They are often called the stakeholders. The next section describes the stakeholders involved in construction supply chains in more detail.

2.2.5 Stakeholders involved in construction supply chains

The concise Oxford dictionary (1995) defines a stakeholder as *"a person with an interest or concern in something"*. In broader sense, to suit the context of the construction industry, construction supply chain stakeholders can be defined as people, parties or organisations which are involved and have interest in construction supply chains. In general, the stakeholders are client/owner, main contractor, suppliers, subcontractors and the design team.

A more detail classification of the stakeholders involved in the construction supply chain has been proposed by Edum-Fotwe *et al* (1999). He argues that the stakeholders

involved in the construction supply chain may vary according to the stage of the construction as summarized in table 2-10 below.

Table 2-10 Stakeholders involved in the construction supply chain (Edum-Fotwe et al., 1999)

Conceptual	Construction	Maintenance	Replacement	De-commission
Client Project manager Safety/quality consultant Architectural designers Civil designer Structural designer Mechanical designer Electrical designers Specialist designers Cost consultant Financial institution Insurance agency Regulatory bodies	Main contractor Domestic subcontractors Nominated subcontractors Project manager Material suppliers Plant/equipment suppliers Designer Financial institution Insurance agency Regulatory bodies	Client In-house management Maintenance contractors Facilities consultant Insurance agency	Client Project manager Safety/quality consultant Architectural designers Civil designers Electrical designers Specialist designers Cost consultant Regulatory bodies Main contractor Domestic subcontractors Nominated subcontractors Material suppliers Plant/equipment suppliers	Demolition contractor

To have a common perception and understanding of the main stakeholders in the construction supply chain, the definitions of client, main contractor, subcontractors and supplier are explained briefly as follows;

1. Clients

A client is a very important element of any construction project. He/she is the initiator of a construction project, the one who makes the initial decision to procure a construction work and decides the procurement system (Briscoe et al., 2004). To build a construction project, he/she needs to employ a contractor which can be selected either by negotiation (partnering) or competition (tender) (Baldry, 1996). This shows that a client has a strategic position which may influence the whole project through his decisions on setting up the project and procurement system (Bresnen and Haslam, 1991). Due to his position, clients also are considered to be the most important key factor in the success of supply chain integration (Briscoe et al., 2004).

The way in which a client makes a decision is heavily influenced by his/her level of experience (Bresnen and Haslam, 1991). In addition, a client's previous construction experience has also significant impact on the interaction process between him/herself and construction professionals, e.g. contractor, designer (Gameson, 1996).

There are various types of clients in the construction industry. Gameson (1992) classifies clients in the construction industry based on two characteristics, namely whether they are primary or secondary constructors and their level of construction experience. Primary clients are clients whose main business and primary income derived from constructing buildings, such as property developers. Secondary clients are clients whose expenditure on constructing buildings is a small percentage of their total turnover, and they need the buildings to run a specific business activity, such as manufacturing. Based on the levels of construction experience, clients can be classified as inexperienced and experienced. Inexperienced clients are clients who have *"no recent and relevant experience of constructing buildings, with no established access to construction expertise"*. Experienced clients are clients who

have *"recent and relevant experience of constructing certain types of buildings, with established access to construction expertise either in-house or externally"*. As previously mentioned, these types of clients will inevitably influence on their way of making decision and interaction process between clients and construction professional, which in turn may impact on the project performance.

2. Main Contractor

The main contractor plays a significant role in the project's success. He is responsible for the completion of the project to a pre-determined time, cost and quality. In construction supply chains, he has a strategic position as a 'facilitator' to manage demand from the client/design team and supply from suppliers or subcontractors (Cox et al., 2006).

The process of selecting subcontractors and suppliers is normally carried out by the main contractor before the project starts. However, not all subcontractors and suppliers need to undergo selection by a main contractor the obtain contracts. They may be nominated by the client, often with advice from the designer. Some reasons for nominating a subcontractor (Banwell, 1964) in (Muya, 1999), include: the need for specialist techniques from a specialist subcontractor, the need to place order for specialist work at an earlier time before the main contractor is selected, and a particular quality of work which a specialist subcontractor may offer.

3. Subcontractors

Subcontractors play important roles in construction projects. They help the main contractor to carry out specialist works. It is not uncommon for as much as 90% of a construction project to be subcontracted (Matthews et al., 2000) and consequently that subcontractors may contribute as much as 90% of a main contractor's turnover (Ndekuri, 1998). This shows the important position and contribution of subcontractors to the main contractor and the success of the project.

Subcontractors' early involvement in a project allows a better understanding of the project itself and helps the overall relationship with the main contractor, which promotes trust and team working between parties (Matthews et al., 1996). It should be noted, that a good relationships between a main contractor and its subcontractor has been considered as a great strategic asset for both of them (Kale and Arditi, 2001).

4. Suppliers

In general, suppliers are parties who supply materials to a construction project. Oswald and Burati (1992) define a supplier as *"Any enterprise that enters into a contract with a main contractor, a project manager or a client to: supply, manufacture and supply, or to manufacture, supply and erect or install construction materials, products or component the organisation itself supplies"*.

Suppliers play important role on a construction supply chain. They supply materials or components for construction projects in time and at reasonable cost (Venkataraman,

2004), which can reach value as much as 50-60% of the total cost of the project (Stuckhart, 1995). Delivering on time may lead to shorter cycle time, inventory level reduction and improving service level (Venkataraman, 2004). These justify the importance of managing suppliers along the construction supply chain to obtain good performance of a construction project.

All in all, clients, main contractors, subcontractors and suppliers play important roles on the success of construction supply chains as they have strategic positions on the construction supply chains. Yet, to successfully manage the construction supply chains, they have to face many problems in the construction industry and construction supply chains, which will be discussed in more detail in the next section.

2.2.6 Problems in the construction industry and construction supply chains

As previously mentioned, the construction industry suffers from many problems, e.g. low profit margin, delays, budget overruns, and is beset with claims and counter-claims (Yeo and Ning, 2002). It was also reported that the typical contractor-subcontractor relationship is still traditional, arms-length, cost-driven and potentially adversarial (Greenwood, 2001). In addition, Agapiou *et al.* (1998) reported that in the UK since 1990 tender prices have reduced by 24% and profit margin on construction work is as low as 1-2% of the construction price. Delays which are common problems in construction, are reported to result in lower productivity (Christian and Hachey, 1995) and increase costs (Alkass et al., 1995). It has also been reported that 52% of UK construction projects end up with claims of some type (Conlin and Retik, 1997). Waste was also identified in many construction projects as a result of ineffective construction processes (Alarcon, 1997, Serpell, 1997).

Problems in the construction industry may also be seen from demand and supply perspective as proposed by Cox and Townsend (1998). He concluded that the problems in construction supply chain can be categorised in terms of demand, supply and common issues.

Demand issues include problems with low and discontinuous demand, frequent changes in specification, inappropriate selection criteria, and inappropriate allocation of risk.

- *Low and discontinuous demand.* These problems may be caused by the difficult financial situation due to economic recession which declines the number of public investment as a result.
- *Frequent changes in specification* by a client is reported frequently occur when a scheme is underway, and which may have serious implication in terms of cost and programme.
- *Inappropriate selection criteria* refers to the common practice in the construction industry of awarding a contract to the contractor with the lowest price, not the best value. As a consequence, the winner may provide a lower standard of service and quality which may result in bigger problems for the

client, e.g. claims for additional fees, a resistance to design changes, less trust, etc.

- *Inappropriate allocation of risk* refers to the unfair distribution of risks in the project between the client and the main contractor.

Supply issues include poor quality, inefficient methods of construction, and poor public image, as described below:

- *Poor quality* is a major problem in the construction industry as reported by (Latham, 1994). The poor quality stems from the low barriers to entry to the construction industry. This means that a newly-established construction company may enter the industry easily with no qualifications or experience. This may be bad for consumers and damaging to the quality and reputation of the industry.
- *Inefficient method of construction* has been reported as occurring, especially in the house-building sector in the UK. One way to overcome this practice is by integrating the design with the construction method to improve the buildability of a project.
- The construction industry has *poor public image*. It has failed to attract and retain high calibre personnel and also has many problems, e.g. poor pay, dangerous, unhealthy, unpleasant, poor job security, uncertain working hours and unequal opportunities concerning the employment of women.

The common issues include poor management, inadequate investment, adversarial culture, and fragmented industry structure.

- *Poor management* may occur either at company level or at site level and can lead to poor performance.
- The *inadequate investment* in training, research and development has become a problem in the construction industry and this may impact on quality in the industry. The low level of in the workforce due to lack of training will certainly impact on the quality.
- *Adversarial culture*. This has been a recognised problem for many years and may result in disadvantages for both clients and contractors and discourage the adoption of the best modern procurement processes.
- *Fragmented industry structure*. The fragmentation is not only in terms of the number and size of construction firms, but also the diversity of professions and trades. Many main contractors no longer undertake work directly. This leads the main contractors to subcontract the work to specialist subcontractors, hire plant, use labour-only subcontractors and use many suppliers. The use of subcontractors that may further subcontract their work and the use of labour-only subcontractors with little or no training could easily exacerbate the problem.

An effort to identify problems in the more specific context, i.e. construction supply chains, has been done by Vrijhoef (1998). From his literature review and case studies, he identified 10 basic problems in contemporary construction supply chains as summarised in table 2-11 below.

Table 2-11 Ten basic problems in contemporary construction supply chains (adapted from Vrijhoef (1998))

Basic problems	Description
Incoherence of the supply chain	Temporary project organisation, separation between design and production Lack of common objective and future orientation.
Non-transparency and lack of insight in the supply chain	Complexity and fragmentation of the construction process, illogical and complex procedure. Inter-organisational barriers, misunderstanding
Bad controllability of the supply chain	Uncertainty and variability, converging logistics to one site, delays, unclear and ineffective distribution of responsibilities and authorities. Non-synchronicity of sub-processes, too large span of control, large inventories used as safety stocks
Ineffective management methods	Traditionalistic operations and materials management, "schedule-push" Obsolete control methods, separate planning
Lack of communication and information exchange	Reduced recognition of the importance of communication, inferior information systems Ineffective communication, no systematic feedback of problems
Lack of collaboration and involvement	Lack of involvement of suppliers and subcontractors, insufficient involvement and cooperation regarding improvement activities Non-collaborative working relations, lack of support, not informing stakeholders about improvement activities, separate decision making
Confronting culture and adversarial behaviour	Unhealthy contracts, uncertainty about continuation of contracts, unfair distribution of risks, cut-throat procurement methods, adversarial negotiating, conflicts Lack of trust and confidence, price sensitiveness, reduced willingness to share, opportunism, prevailing self-interest
Lack of commitment to the supply chain	Lack of long-term relationships and partnering, reduced consideration of downstream effects of upstream decisions Non-responsiveness to needs of other supply chain participants, ignorance, lack of incentive and funds for innovations and product development
Absence of supply chain perspective	Lacking customer focus towards the end user, lacking recognition of the dependencies across the supply chain Lacking conception of supply chain process, underestimation of interdependence
Absence of accurate performance data and adequate assessment methods	Insufficient understanding of performance, lack of measurement and monitoring of performance, underdeveloped analysis methods, insufficient consideration of the total scope of the supply chain Inability to identify and locate waste and problems, unawareness of improvement potential, invisibility of probable benefits of improvement, resistance to change

In addition, Alarcón *et al.* (1999) observed that the most frequent problems on procurement were: delay at delivery, delay on ordering, repair and replacement at job site (equipment), poorly planned inspections (equipment supplier), lack of information on site about arrival for some supplies, delays on engineering (programming) and frequent changes to air transportation to make faster deliveries. He found the main sources for these problems were the system itself (form and procedure to carry out works), engineering (delays, errors, etc), company policies and the suppliers. An analysis of the value stream of the procurement process for an industrial project showed that only 18% of the activities were found to be value adding.

In short, problems in construction supply chains are in line with the existing problems in the construction industry. They are likely to become classical problems which are

not easy to cope with. Some obstacles from inside the construction industry itself may cause the effort to eliminate these problems and improve performance to become even harder, as Vrijhoef (1998) says "*One of the major obstacles in construction regarding performance improvement is the lacking availability and accessibility of performance data. Keeping performance registers, for instance, is a rare event. Construction firms have often been criticised that they don't know what they don't know.*"

2.3 Comparing SCM in manufacturing and construction

Considering that manufacturing and the construction industry have many different characteristics, supply chain management in both industries are obviously different. The construction industry is project-based with temporary organisation and fragmented, converging supply chains, etc. A construction project can also be considered as a product which is fixed position manufacturing and rooted in place (Ballard and Howell, 1998).

From perspective of the product, the process in manufacturing can be considered separate from the product. The raw materials are processed and leave the factory in the form of finished product. In construction, the process is relatively inseparable from the end product since the building 'grows' with the methods, techniques and organisation attached to it (Scott et al., 1995) .

Venkataraman (2004) illustrates a comparison of typical supply chain for a make–to-stock manufacturing company and for a project organization as shown in figure 2-9. Each organization in the supply chain has inbound and outbound component. Inbound component may consist of suppliers or raw materials and components, along with transportation links and warehouses and ends with the internal operation of the company. Outbound component begins when the organization deliver its output to immediate customer and may include wholesalers, retailers distribution centres, transportation companies and ends with the final customer. In the make–to-stock manufacturing company, the inbound supply chain is normally shorter than the outbound. On the other hand, in the supply chain for a project organization, the inbound supply chain is normally longer than the inbound.

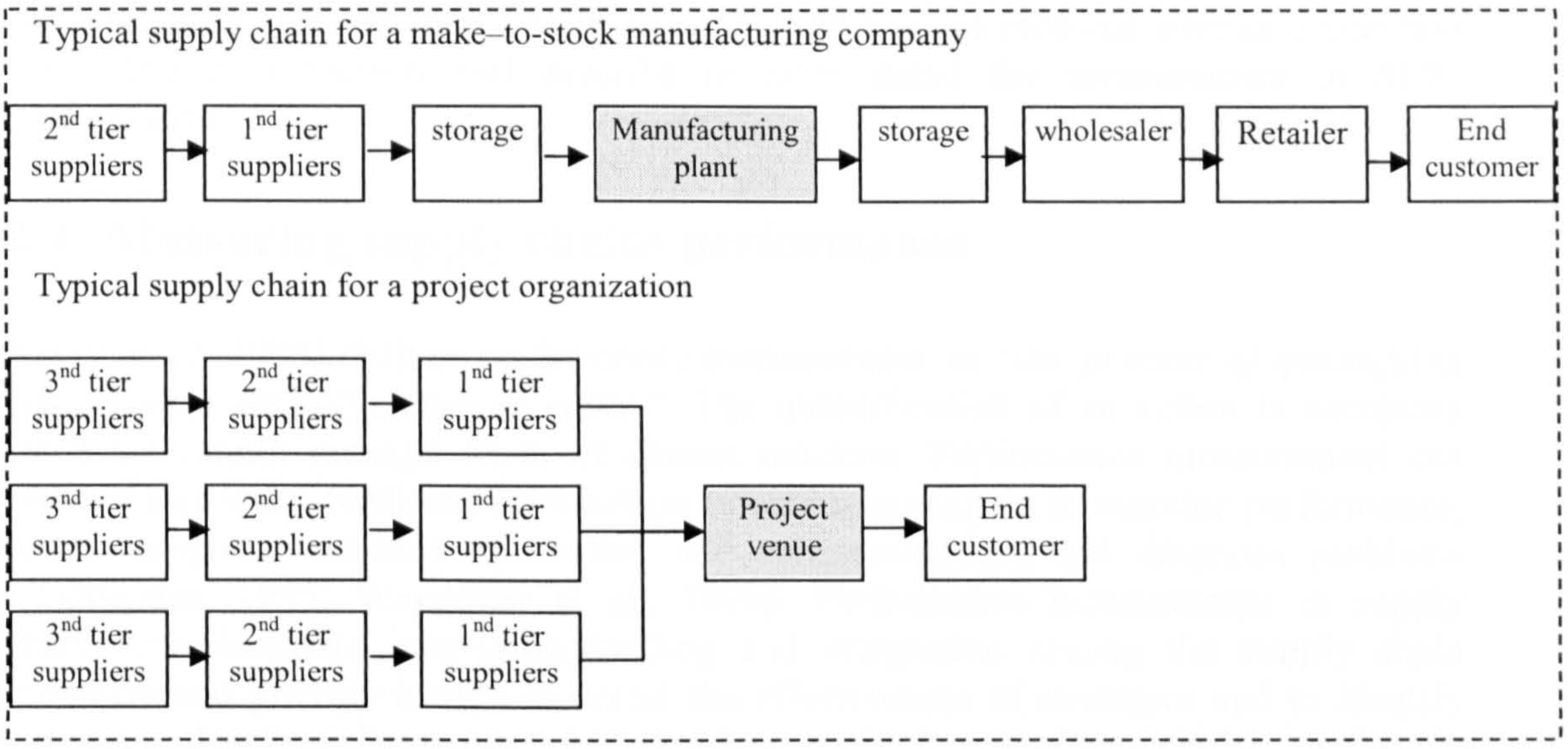


Figure 2-9 Typical supply chain for a make–to-stock manufacturing company and for a project organization (Venkataraman, 2004)

Another piece of work with different perspective was carried out by Ghurka (2003) who summarises the differences between traditional or manufacturing supply chain and construction supply chain, as shown in table 2-12 below.

Table 2-12 Comparison of traditional/manufacturing and construction supply chain (Ghurka, 2003)

Traditional/Manufacturing SC	**Construction SC**
Build to stock is widely used model (e.g. apparels, automotive, consumer goods, etc)	Build to order is the widely used
Wider and less specific end product	Specific and defined end product
High degree of standardization with repeatability	Project-unique design and material specifications with little or no repeatability
Reliable demand forecast and planning can be done	Uncertain demand forecast and inadequate tools
Generally only one organization is responsible for the production process	Multiple organization with different objectives involved in the production process
Predefined supplier and distribution network	Project-specific suppliers and distribution network
Many suppliers supplying to a wide range of end users	Many suppliers supplying to a specific end user

All in all, it is clear that there are significant differences between the construction and manufacturing industry as well as the supply chains. The differences can be found in either pre-construction, construction or post-construction phase. These differences will inevitably bring the attention to researchers when using supply chain management literature from the manufacturing industry to be applied to the construction context.

As previously mentioned, supply chain management is a recent topic which received attention from many researchers over the last decade. However, the discussion of performance measurement on SCM is considered has not received adequate attention yet. The next section will describe in more detail the measurement of SCM performance.

2.4 Measuring supply chains performance

Neely *et al* (1995) defines performance measurement as "*the process of quantifying effectiveness and efficiency of action*". The quantification of an action is necessary since we cannot manage what we cannot measure. Performance measurement can provide important feedback information to enable managers to monitor performance, reveal progress, enhance motivation and communication, and diagnose problems (Rolstandas, 1995, Waggoner et al., 1999). Performance measurement in supply chains can facilitate inter-understanding and integration among the supply chain members and provide insight to reveal the effectiveness of strategies and to identify success and potential opportunities. In other words, it provides necessary assistance for performance improvement in pursuit of supply chain excellence. However, it is not always easy to measure performance of an action or process. Establishing the right parameters of measurement and obtaining the relevant data can be very difficult and frustrating as Sink (1991) argues "*Measurement is complex, frustrating, difficult, challenging, important, abused and misused*".

2.4.1 Supply chain performance measurement in the manufacturing industry

Some researchers have addressed performance measurement issues of supply chains in the manufacturing industry, e.g. (Beamon, 1999, Gunasekaran et al., 2004, Al-Khalil et al., 2004, Otto and Kotzab, 2003). Table 2-13 shows some of the important supply chain performance measures that have been reported in the literature by Bhatnagar and Sohal (2004). From these performance measures, they argue that "*there is no a stable set of measures that can be used for assessing performance of supply chain in all contexts*". These measures tend to be related to inventory, quality, flexibility, lead time, and customer service.

Table 2-13 Measures of supply chain performance identified in the literature (Bhatnagar and Sohal, 2004)

Author	Performance measures
Levy (1995)	Average finished goods inventory Demand fulfilment
Christopher (1992)	Order cycle time Order completeness Delivery reliability
Lambert and Sharman (1990)	Delivery performance Lead time Level of defects Responsiveness
Cohen and Lee (1990)	Material inventory Work in process inventory

Author	Performance measures
	Finished goods inventory Fill rates Stockout frequencies Lead time
Lee and Billington (1992)	Inventory turns Line item fill rate Order item fill rate Total order cycle time Total response time to an order Average backorder levels Average variability in delivery

The performance measures listed above mainly relate to the operational level of SCM and cover the period from 1990 to 1995. To up date this list, some examples of recent supply chain performance measures reported in the literature are reported below.

Beamon (1999) argues that a supply chain measurement system must place emphasis on three separate types of performance measure, i.e. resource measures (R), output measures (O), and flexibility measures (F). He argues that the supply chain performance measurement system must measure each of these three types, as each type is vital to the overall performance success of the supply chain. The reasons for this are said to be: efficient resource management is critical to profitability (R), customers will turn to other supply chains without acceptable output (O), supply chains must be able to respond to change in an uncertain environment (F). Table 2-14 shows the three types of measures with their components.

Table 2-14 SCM performance measures (Beamon, 1999)

Resources	**Output**	**Flexibility**
• Inventory levels • Personnel requirement • Equipment utilization • Energy usage • Cost	• Sales • Profit • Fill rate • On-time deliveries • Backorder/stockout • Customer response time • Manufacturing lead time. • Shipping errors. • Customer complaints.	• Volume flexibility • Delivery flexibility • Mix flexibility • New product flexibility

A different approach has been proposed by Otto and Kotzab (2003) who developed performance metrics of SCM based on six perspectives, i.e. system dynamics, operation research, logistics, marketing, organization and strategy, as shown in table 2-15 below. With these six perspectives, it is said that a set of comprehensive and holistic metrics to assess the supply chain may be established.

Table 2-15 Performance metrics of SCM base on six measurement perspectives (Otto and Kotzab, 2003)

System Dynamics	Operations Research	Logistics	Marketing	Organization	Strategy
• Capacity utilization • Cumulative inventory level • Stock-outs • Time lags • Time to adapt • Phantom ordering	• Logistics costs per unit • Service level • Time to deliver	• Integration • Lead times • Order cycle time • Inventory level • Flexibility	• Customer satisfaction • Distribution costs per unit • Market share/channel costs	• Transaction costs • Time to network • Flexibility • Density of relationships	• Time to network • Time to market • ROI of focal organization

Another piece of research in this area was carried out by Gunasekaran *et al.* (2004). He developed a framework for measuring SCM performance which evaluates the order planning, supply link, production level, delivery link, customer and service satisfaction and cost of supply chain and logistics as shown in table 2-16. This framework places emphasis on the wide and complete performance measurement of supply chains which is said to be cross functional and intra-organisational as he argues *"A performance measurement program for a supply chain should be complete—important aspects of performance in any link are not ignored—and they must be tailored to varying needs of participants"*.

Table 2-16 A framework for measuring SCM performance (Gunasekaran et al., 2004)

Metrics for order planning	Evaluation of supply link	Measures and metrics at production level	Evaluation of delivery link	Measuring customer service and satisfaction	Supply chain and logistics cost
• The order entry method • Order lead time • The customer path	• Evaluation of suppliers • Strategic level measures • Tactical level measures • Operational level measures	• Range of product and services • Capacity utilization • Effectiveness of scheduling techniques	• Measures for delivery performance evaluation • Total distribution cost	• Flexibility • Customer query time • Post transaction measures of customer service	• Cost associated with assets and return on investment • Information processing cost

These examples of different approaches show that performance measures may vary among authors depending on the goals, areas, levels and scope. Otto and Kotzab (2003) say they should be tailored as *"different approaches to SCM lead to different awareness of what should be measured to assess performance"*. It is argued that one organisation's measures might not be appropriate for others. In order to reveal a real insight of supply chain performance, the appropriate performance measures that best suit the supply chain context are required.

The supply chain measures discussed above are mainly in the context of the manufacturing industry, from which SCM theories were initially originated. It should be noted that there is a clear gap in supply chain practice between the manufacturing and the construction industries (Naim, 1997). The next section will discuss further the measures of supply chain performance in the construction industry.

2.4.2 Supply chains performance measurement in the construction industry

Measuring performance in construction was said by Proverbs and Holt (2000) to be a complicated process and to date, there have been few researchers who have focussed their research specifically on measuring supply chain performance in this industry. Vrijhoef (1998) reported some attempts to do this in the previous literature as presented in table 2-17 below. The work listed relates to materials management effectiveness, logistic processes, productivity and supply chain processes.

Table 2-17 Assessment efforts of construction supply chains (Vrijhoef, 1998)

Variable(s)	Assessment method	Author(s)
Materials management effectiveness	Benchmarking process effectiveness	Plemmons et al. (1995)
Time, costs, accuracy, and delivery times of logistic processes	Analysis of logistic processes	Wegelius-Lehtonen (1995)
Variation, interruptions, and disruptions of productivity	Analysis of variations	Smith et al. (1996)
Deviations in the supply chain process	Identification of deviations	Formoso et al. (1996)
Delays along the supply chain process	Definition and classification of delays	Lewis et al. (1996)
Lead times, deliveries, production costs and uncertainty	Integrated cost and performance analysis	O'Brien (1997)

To update Vrijhoef's lists, some more recent research on supply chain management performance measurement has been identified in the literature and will be reported here. Other types of measure have been suggested by Wegelius-Lehtonen (2001). He offered a framework for performance measurement in construction logistics. This framework has 2 dimensions to classify performance measures, which were: *use of measure* and *focus of measure*. *Use of measure* reveals the application area where the measures are to be used, i.e. *improvement* and *monitoring measures*. The *improvement measures* are vital for new development and cooperation projects whose aim to find out the present logistical performance level and improvement potential. The *monitoring measures* are needed for screening and controlling day to day operation of a company. *Focus of measure* illustrates the organisation level where the measures are to be used, i.e. general company or project level, and specific subcontract or material supplier level. The reason for this classification is that different levels of organization need different measures. In terms of construction logistics, measures can be used in three levels; i.e. logistics performance at company level, individual projects'

performance and performance focused on special subcontractors and material suppliers. This performance measurement framework is shown in figure 2-10 below.

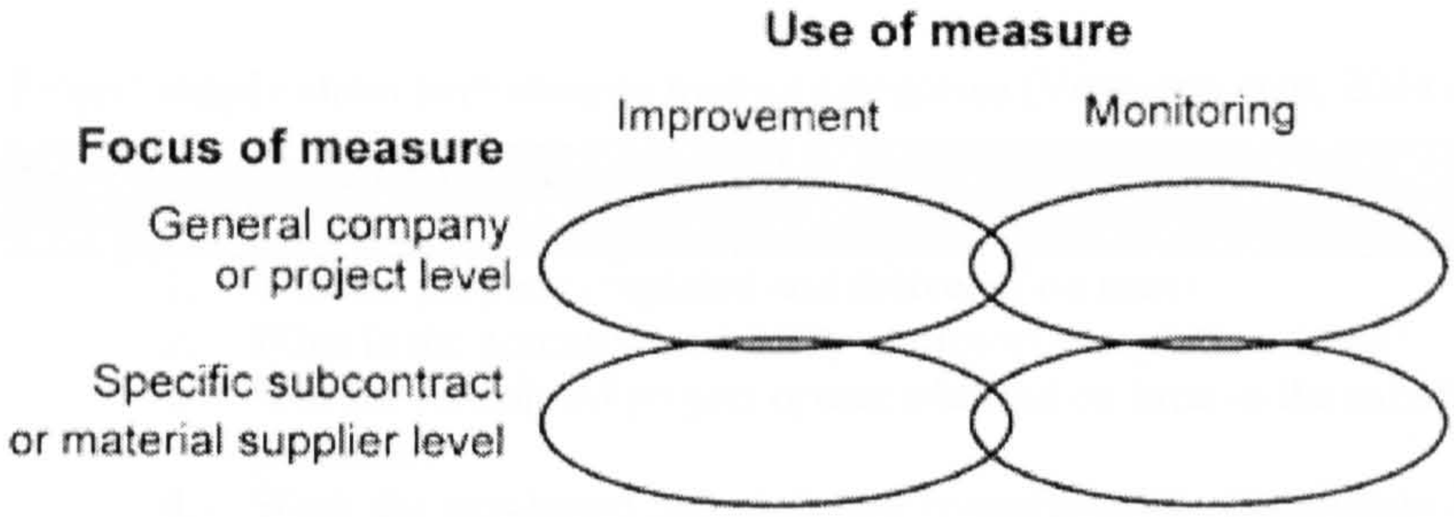


Figure 2-10 Dimension of performance measurement system by (Wegelius-Lehtonen, 2001)

Another piece of research in this area was carried out by Al-Khalil *et al.* (2004) who adopted 12 key effective measures initially proposed by Plemmons and Bell (1995) to measure the effectiveness of materials management for industrial projects. These are classified using five attributes as shown in table 2-18 below.

Table 2-18 Key effectiveness measures (adapted from Al-Khalil *et al.* (2004))

Attribute	Measures	Measured by
Accuracy	Materials receipt problems	percentage of line items received without discrepancy
	Warehouse inventory accuracy	comparing a statistical sampling of the data in the materials database with the physical assets in the warehouse and controlled lay-down areas
Quality	Jobsite rejections of tagged equipment	The percentage of all rejections of tagged equipment.
Timeliness	Procurement lead time	ratio of the average procurement lead time in days and the planned procurement lead time
	Bid/evaluate/commit lead time	the average duration reported in days to bid, evaluate, and commit (BEC) to the purchase of materials relative to the planned duration
	Purchase order to material receipt duration	It is the ratio of the average duration to planned duration
	Materials receiving processing time	percentage of material received by the warehouse that is processed within two time periods: same day and next day
	Commodity vendor timeliness	Percentage of vendor deliveries that were delivered on time.
	Materials withdrawal request lead time	Ratio of the average MWR lead time and the planned MWR lead time.
Cost	Construction time lost	percentage of construction time lost due to the impact of materials as estimated by construction supervisors
	Total surplus	the percentage value of unused materials in relation to the total purchase cost of materials
Availability	Materials availability	$\frac{\text{Total no of material line items issued}}{\text{Total no of material line items requested}}$

In line with Al-Khalil *et al.* (2004), Venkataraman, (2004) proposed some metrics for project supply chain performance which he classified using four categories, i.e. time, cost, quality and flexibility, as shown in table 2-19. Apart from flexibility category, the other three categories i.e. time, cost and quality are similar to those used by Al-Khalil *et al.* (2004).

Table 2-19 Project supply chain performance metrics categories (Venkataraman, 2004)

Performance category	**Performance issues**
Time	1. Was the project completed and delivered on time? 2. What is the potential variability in project completion times? 3. Was the completed project operationalised on time to the satisfaction of the customer? 4. Were the purchased materials and manufactured components delivered on time by upstream suppliers? 5. What is the potential variability in procurement lead times?
Cost	1. Was the completed project within budget for each of the project supply chain member? 2. What was the total project supply chain cost? • Procurement cost of purchased materials • Manufacturing cost • Inventory-related cost • Transportation cost • Project acceleration costs • Cost of liquidated damages • Other relevant costs: administrative, etc
Quality	1. Did the project meet the technical specifications and does it provide the functionality desired by customer? 2. Was the customer satisfied with the service provided during start-up, implementation, and final project transfer? 3. Were the purchased raw materials and manufactured components defect-free? 4. Was the completed project's product reliable and durable during its life cycle?
Flexibility	1. Was the customer accorded reasonable freedom within a reasonable time frame to make changes to the project scope, design or specification? 2. Were the upstream suppliers responsive to the reasonable needs of their downstream partners in terms of delivery time and quality issues?

It is worth mentioning that most of the measures described above come from literature studies which some are adopted from literature in manufacturing. In this regard, it is interesting to find out the importance of the measures from the perspective of contractors and suppliers as reported by Muya (1999). He conducted research on construction materials logistics and found that both contractors and suppliers ranked performance indicators in the same order of importance, from the most important (item 1) to the least important (item 5):

1. reliability *(ability of supplier to deliver right products, right quality and quantity on schedule without damage).*
2. cost-effectiveness *(cost of service satisfactory to customer)*
3. flexibility *(responsiveness to changing customer needs)*
4. lead time *(quoted by suppliers)*
5. value-added *(service exceeding basic service requirements)*

It is not surprising that *reliability* was seen as the most important performance indicator by both contractors and suppliers. Clearly both of them realise that reliability in delivering the right product, right quality and quantity on schedule without damage is pre-eminent.

The reliability of the supply of materials will obviously influence the performance of a construction site. Delays in deliveries of materials will delay the construction process on site, particularly if the related activities are on the critical path. The same situation is likely to occur if other flows in the construction supply chains, such as information flow, labour flow, plant/equipment flow, etc, are also delayed. Despite an extensive search of the literature on the quantification of the impact of supply chain management practice on project performance, no relevant references could be found. It was thus decided to investigate these problems by exploring supply chain management practice in the construction industry by simulating its impact on project performance.

Chapter 3
Research Methods

This chapter gives an overview of the existing research methods in the literature, including simulation theory, and describes the research methods adopted in this research, followed by a discussion about triangulation. The chapter is structured as follows:

3.1 Overview of research methods: In this section, four major classifications of research methods are described. Further categorisation of each types of research methods based on these four major classifications are also defined.

3.2 Simulation: This section discusses simulation, one of the methods used in this research. Issues described here include the uses, classifications and steps of simulation, followed by a discussion on simulation software and simulation in the construction industry.

3.3 Research methods adopted in this thesis: Here, the details of the research methods adopted in this thesis are explained. It comprises the preliminary investigations, the main survey, and simulation.

3.4 Triangulation: This section describes the definition of triangulation, and the advantages of adopting it in the research. Different types of triangulation are described, including two which are adopted in this research.

3.1 Overview of research methods

Collis and Hussey (2003) classify types of research on the basis of four categories; i.e. the purpose, the process, the logic and the outcome of the research. The purpose reveals the reason for conducting the research, which can be classified as exploratory, descriptive, analytical and predictive. The process reveals the way in which data will be collected and analysed. According to the process, research can be classified as either quantitative or qualitative. The logic shows whether the research moves from the general to the specific or the other way around. Based on the logic, the research can be classified as deductive or inductive. The outcome of the research can be the solving of a particular problem or to make a general contribution to knowledge. Based on the last category, the research can be classified as applied or basic research. Table 3-1 below summarises the main types of research.

Table 3-1 Classification of main types of research (Collis and Hussey, 2003)

Type of research	Basis of classification
Exploratory, descriptive, analytical or predictive research	Purpose of the research
Quantitative or qualitative research*	Process of the research
Deductive or inductive research	Logic of the research
Applied or basic research	Outcome of the research

*(Creswell, 2003) adds *mixed research* approach to this category

3.1.1 Exploratory, descriptive, analytical and predictive research

Exploratory research looks for patterns, ideas or hypotheses. This kind of research is suitable when there are few earlier studies to which to refer. The question words appropriate for this type of research are: how, why, what, how often, how much, how many, who, what, where.

Descriptive research tries to identify and obtain information characteristics of a particular problem or issue. In other words, this kind of research attempts to describe phenomena as they naturally exist. The appropriate question words for this approach are: who, what, where, how many, how much.

Analytical or explanatory research, which is a continuation of descriptive research, tries to understand phenomena by discovering and measuring causal relations amongst them. This type of research describes, analyses and explains why and how the characteristics are happening. The appropriate question words for this method are: how and why.

Predictive research aims to generalise from analysis by predicting certain phenomena on the basis of hypothesised general relationships. This type of research aims to forecast the likelihood of an occurrence. The appropriate question words here are: who, what, where, how many, how much. Table 3-2 summarises the classification of research methods based on the purpose.

Table 3-2 Classification of research methods according to research purpose (synthesized from Collis and Hussey (2003) and Ellram (1996))

Research type	Description	Aim	Examples of appropriate methodologies	Appropriate Question words
Exploratory	Suitable when there are few or no earlier studies to which we can refer for information	To look for pattern, ideas or hypothesis, rather than testing or confirming a hypotheses	Qualitative • Experiment • Case study • Participation observation • historical analysis	How, why
			Quantitative • Survey • Secondary data analysis	How often, how much, how many, who, what, where
Descriptive	Describe phenomena as they exist	To identify and obtain information on the characteristics of a particular problem or issue	Quantitative • Survey • Longitudinal • Secondary data analysis	Who, what, where, how many, how much
			Qualitative • Case study • Experiment • Grounded theory • Participant observation • Ethnography • Case study	Who, what, where
Analytical or explanatory	A continuation of descriptive research. Describe, analyse and explain why and how the characteristics happening.	To understand phenomena by discovering and measuring causal relations among them.	Qualitative • Experiment • Case study • Grounded theory • Participant observation • Ethnography • Case survey	How Why
Predictive	Forecast the likelihood of an occurrence	To generalise from analysis by predicting certain phenomena on the basis of hypothesised general relationships.	Quantitative • Survey • Longitudinal • Secondary data analysis	Who, what, where, how many, how much
			Qualitative • Case study • Experiment • Grounded theory • Participant observation • Ethnography • Case survey	Who, what, where

3.1.2 Qualitative and Quantitative Research

Based on the research process, research can be classified as quantitative and qualitative. Creswell (2003) defines the *quantitative approach* as a research method '*in which the investigator primarily uses postpositivist*[1] *claims for developing knowledge (i.e. cause and effect thinking, reduction to specific variables and hypotheses and questions, use of measurement and observation, and the test of theories), employs strategies of inquiry such as experiments and surveys, and collects data on predetermined instruments that yield statistical data'*. Quantitative research is objective in nature and focuses on measuring phenomena by collecting and analysing numerical data and applying statistical tests (Creswell, 2003). This is a deductive approach, which is more appropriate for mature subjects or research areas and more appropriate for questions like what and how many. The results are likely to be precise, measurable and easy to understand. However, the result will be limited to what we intend to look for. Results that do not fit assumptions are hard to find since the models are not designed to measure it (Yin, 1994).

Qualitative research is defined as '*one in which the inquirer often makes knowledge claims based primarily on constructivist*[2] *perspectives (i.e. the multiple meaning of individual experiences, meanings socially and historically constructed, with an intent of developing a theory or pattern) or advocacy/participatory perspectives (i.e. political, issue-oriented, collaborative or change oriented) or both*' (Creswell, 2003). Qualitative research is more subjective in nature and involves examining and reflecting on perceptions to gain an understanding of social and human activities (Collis and Hussey, 2003). This method is an inductive approach which is appropriate for relatively new subjects or research areas where definitions are still unclear and is more appropriate for question like what and why (Yin, 1994).

In addition to these approaches, Creswell (2003) adds a *mixed methods* approach to this category. He defines the *mixed methods* approach as *'one in which the researcher tends to base knowledge claims on pragmatic grounds (e.g. consequence-oriented, problem-centered, and pluralistic)'*. In order to best understand the research problem, this approach employs strategies of inquiry that involve collecting data either simultaneously or sequentially, and using numeric as well as text-based information. Table 3-3 below summarises these three approaches in more detail.

---

[1]Postpositivits view that the reality out there can only be approximated, can never be fully apprehended (Guba, 1990) and stress on the discovery and verification of theories (Denzin and Lincoln, 1994).
[2] To constructivists, the reality is not seen as it is, rather we see it as we are. What we accept as reality is actually a construction of our mind. *"Constructivists view people as constructive agents and view the phenomenon of interest (meaning and knowledge) as built instead of passively 'received' by people whose ways of knowing, seeing, understanding, and valuing influence what is known, seen, understood, and valued"* (Spivey, 1997).

Table 3-3 Qualitative, quantitative and mixed method approaches (Creswell, 2003)

	Qualitative approach	Quantitative approach	Mixed method approach
Philosophical assumption	• Constructivist • Advocacy • Participatory knowledge claims	• Postpositivist knowledge claims	• Pragmatic knowledge claims
Strategies of inquiry	• Phenomenology • Grounded theory • Ethnography • Case study • Narrative	• Surveys • Experiments	• Sequential • Concurrent • Transformative
Methods	• Open ended questions • Emerging approaches • Text or image data	• Closed-ended questions • Predetermined approaches • Numeric data	• Both open- and closed-ended questions • Both emerging and predetermined approaches • Both quantitative and qualitative data and analysis
Practice of research	• Position himself or herself • Collects participant meanings • Focuses on a single concept or phenomenon • Brings personal values into the study • Studies the context or setting of participants • Validates the accuracy of findings • Makes interpretations of the data • Creates an agenda for change or reform • Collaborates with participants	• Test or verifies theories or explanations • Identify variables to study • Relates variables in questions or hypotheses • Uses standards of validity and reliability • Observes and measures information numerically • Uses unbiased approaches • Employ statistical procedures	• Collect both quantitative and qualitative data • Develops a rationale for mixing • Integrates the data at different stages of inquiry • Presents visual pictures of the procedures in the study • Employs the practices of both qualitative and quantitative research

3.1.3 Deductive or inductive research

Based on the logic, research can be classified as deductive or inductive. Collis and Hussey (2003) define *deductive research* as a study in which a conceptual and theoretical structure is developed and then tested by empirical observation where particular instances are deduced from general inferences. In other words, it is moving from the general to the particular. *Inductive research* is a study in which theory is developed from the observation of empirical reality. In contrast to *deductive research*, general inferences are induced from particular instances. It moves from the specific to the general.

3.1.4 Applied or basic research

Based on the outcome, research can be classified as applied or basic research. *Applied research* is research whose findings are designed to solve a specific problem. *Basic research* is research which is conducted primarily to improve our understanding of general issues, without emphasis on its immediate application. Because of its principle of making a contribution to knowledge in general, *basic research* is regarded as the most academic form of research (Collis and Hussey, 2003).

3.2 Simulation

As will be discussed in section 3.3, simulation is one of the methods used in the research reported in this thesis, and it will be discussed in this section.

3.2.1 Definitions

Simulation is defined as *"the process of creating and experimenting with a computerized mathematical model of a physical system"* (Chung, 2004). Here, a system is defined as *" a collection of interacting components that receives input and provides output for some purpose"* (Chung, 2004). Examples of systems include: aiport operations, port shipping operations, train and bus transportation, distribution and logistics, etc. Other authors recognise simulation as a dynamic, comprehensive technique that provides a true representation of the output behaviour as it evolves over time (Ammar and Mohieldin, 2002) and can determine output based on variations in input (Halpin and Riggs, 1992). Simulation is praised for its ability to study a real world system in detail and to address the random and dynamic features in the operation of the system (Shi, 2002). In terms of research methods, simulation is an example of an experiment which is classified as a quantitative research method (Yin, 2003).

As suggested by the definition above, simulation is one way of studying a sytem. In reality, there are different ways of studying a system (Law and Kelton, 2000) as mapped out in figure 3-1 below. They will be described briefly.

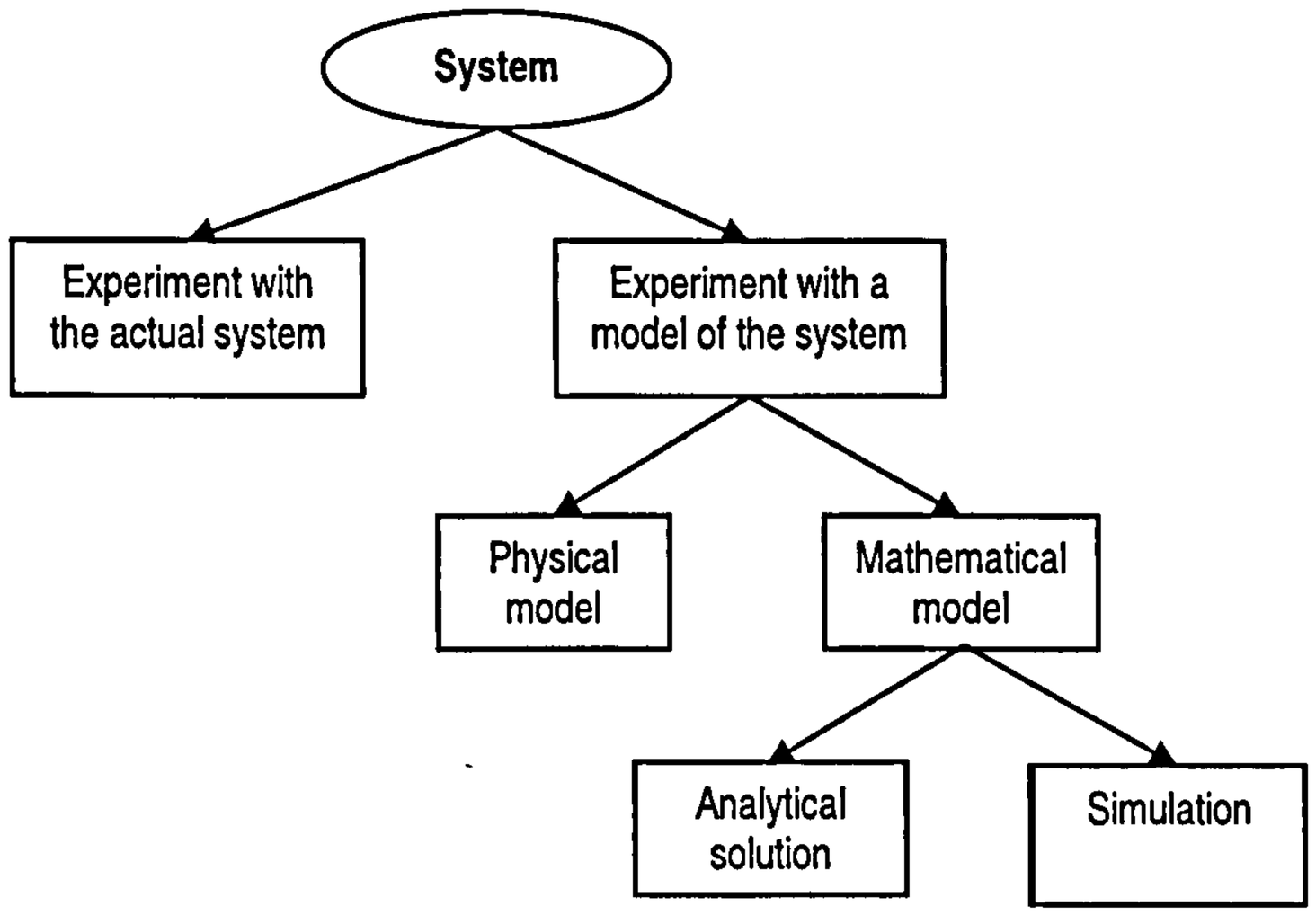


Figure 3-1 Ways to study a system (Law and Kelton, 2000)

- *Experiment with the actual system vs experiment with a model of the system.* If it is possible to alter the system physically and cost-effectively, experimenting with the actual system is probably more desirable, as in this case there is no question about the validity of the model. However, it is rarely feasible to do this, as such an experiment would be too expensive or too disruptive to the system. For these reasons, a model can be built as a representation of the system and the model can be studied as a substitute for the actual system.

- *Physical model vs mathematical model.* Clay cars in wind tunnels, cockpits used for pilot training, or miniature models of a supertanker in a swimming pool are examples of physical models, which are also called *iconic models*. Unlike physical models which can be physically seen and touched, a mathematical model represents *"a system in terms of logical and quantitative relationships that are then manipulated and changed to see how the model reacts, and thus how the system would react"*.

- *Analytical solution vs simulation.* Once a mathematical model is available, a solution can be obtained through an analytical solution or a simulation. If the model is simple enough, an analytical solution may be more desirable, however, many systems are highly complex, so that valid mathematical models of them are themselves too complex to be solved analytically. In this situation, the mathematical model must be studied by means of simulation (hence called *simulation model*), i.e. "*numerically exercising the model for the inputs in question to see how they affect the output measures of performance*".

3.2.2 Uses and advantages of simulation

In the early years, simulation was used mainly by military services, ranging from evaluations of maintenance policies to large scale war games. As it is rapidly growing in popularity, many successful examples of the application of simulation are found in many areas, as shown in table 3-4 below.

Table 3-4 Examples of application of simulation (adapted from Pidd (2004))

Application area	Example of simulation
Transport	Airport management
	Air traffic control
	Harbour management
	Movement of crude and refined oil around the world
	Traffic movement in the UK-France channel tunnel
Manufacturing	Design of manufacturing plant and systems
	Material handling
	Ship building
Health care	Distribution of antibiotics and vaccines in the event of terrorist attack
	Effective and efficient movement of goods and equipment in a new large hospital
	Emergency plan for evacuating patients in hospital
Business Process Reengineering (BPR)	BPR in the UK financial service industry
	Simulation of office processes to achieve target performance level
Defence	Logistic operations
	Battle simulations

There are many advantages of using simulation as described by Chung (2004) below:

1. *Gaining insight into the operation of a system.* As some systems are so complex, it is difficult to understand the operation of and interaction within the system by examining individual components in isolation, without the help of simulation.
2. *Developing operating or resource policies to improve system performance.* Besides allowing an understanding of a system, simulation is also useful for improving the existing system, i.e by changing operating policies, such as different priorities for work orders, or resource policies, such as staffing levels and break scheduling.
3. *Testing new concepts and/or the system before implementation.* A simulation model can help to give an idea of a new system before purchasing or implementing it. The cost of modelling the new system can be very small in comparison with the real investment of procuring equipment for the new system. In addition, using a simulation model, an evaluation can be made on the effects of different levels, expenses and configurations of the equipment.
4. *Gaining information without disturbing the actual system.* Some systems are so critical or sensitive that making any changes to the system is not possible. For example, it is not possible to experiment with the operating policy or resource level in a security checkpoint at a commercial airport, as it would have a serious impact on the operational capability or security effectiveness of

the system. Simulation models make the experimentation on such critical system possible.

5. *Experimentation in compressed time.* The use of computers allows the experimental simulation to be run in compressed time. Multiple replications of each simulation run can also be done easily in seconds to increase the reliability of the analysis.

6. *Reduced analytic requirements.* Without the simulation, one is forced to use more analytically demanding tools, which allow only simple systems to be analysed using a static approach at a given point in time. Simulation, in contrast, allows a system to be studied dynamically in real time during simulation runs. The development of simulation-specific software packages has also helped insulate users from many complicated background calculations and programming requirements. This provides the opportunity to analyse many more different types of systems than was previously possible.

7. *Easily demonstrated models.* How the model works can be demonstrated dynamically using animation. It can also demonstrate how the model copes with varying situations, which can also increase the model credibility. Observing flaws in the model logic, also known as *debugging*, can also be done more easily with the help of animation.

3.2.3 Classifications of systems and simulation

Systems can be classified into two categories: *discrete event systems* and *continuous event systems* (Law and Kelton, 2000). A discrete event system is *"one for which the state variables change instantaneously at separated points in time"*. The points in time are the points when an event occurs, while an event is an instantaneous occurence that may change the state of the system. A bank is an example of a discrete event system, as the number of customers in the bank (state variables) change only when a customer arrives or when a customer finishes being served and departs. Other examples of discrete event systems include stores, service centres, manufacturing facilities and transportation centres. In *continuous event systems*, the state variables change continuously with respect to time. A moving aeroplane through the air is an example of a *continuous event system,* as its position and velocity (state variables) change continuously with respect to time. Continuous event systems must be modelled with differential equations. The additional complexity due to the use of differential equations often makes this type of system more difficult to model accurately.

Analogous to the way systems are classified and defined above, simulation can also be classified into two categories, i.e. *discrete event simulation* and *continuous event simulation* (Law and Kelton, 2000). It should be mentioned, however, that a discrete event simulation is not always used to model a discrete event system, and vice versa. The decision to use an approach for a particular system depends on the objective of the study. For example, traffic flow on a freeway can be modelled discretely, if the characteristics and movement of individual cars are important. Alternatively, the traffic flow can also be modelled in the aggregate using differential equations in a continuous model.

3.2.4 Steps in a simulation study

To understand how a simulation study is carried out, figure 3-2 below shows 10 steps in a typical simulation study. It should be mentioned here that although the flowchart shown comes from the literature on simulation in the context of manufacturing industry, it is also likely to be relevant in the context of the construction industry. Each of the steps will be explained as follows:

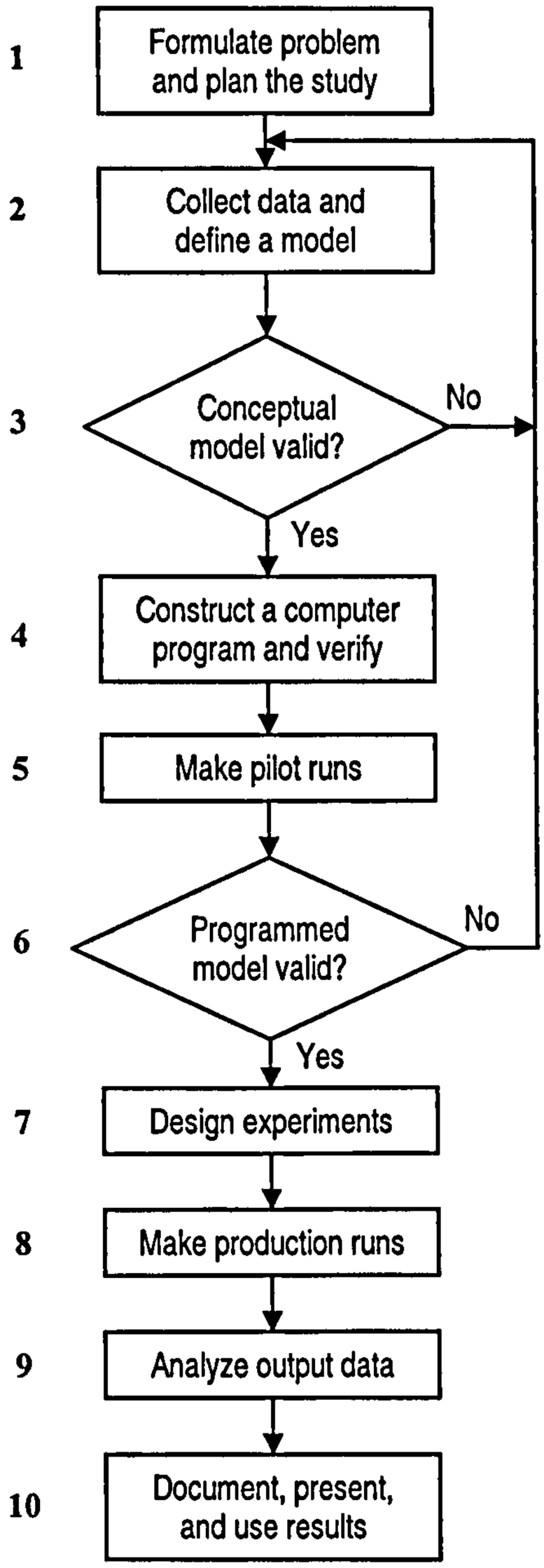


Figure 3-2 Steps in a simulation study (Law and Kelton, 2000)

1. *Formulate problem and plan the study*. Issues to be formulated in the first step include: overall objectives of the study, specific questions to be answered by the study, performance measures that will be used, scope of the model,

system configurations to be modelled, software to be used, time frame and the resources required for the study.

2. *Collect data and define a model.* In this step, data to be collected includes information on the system layout and operating procedures and the data required to specify parameters and input probability distributions (if possible). The above information and data need to be outlined in an *assumption document* (i.e. a report used to record the assumptions made in the simulation model, which is also known as the *conceptual model*). If possible, data should also be collected on the performance of the existing system, which will be useful for validation purposes. In defining the model, the level of model detail should depend on the following: project objectives, performance measures, data availability, credibility concerns, computer constraints, opinions of subject-matter experts, time and money constraints.
3. *Is the conceptual model valid?* This step is carried out before programming begins to ensure that the model's assumptions are correct. Further discussion on validation techniques can be found in section 5.4.2.
4. *Construct a computer program and verify.* This step includes programming the model using a programming language or simulation software and verifying (*debugging*) the simulation computer program. Some verification techniques are described in section 5.4.1.
5. *Make pilot runs.* This is done for validation purposes in step 6.
6. *Is the programmed model valid?* To validate the model, comparison between the model and the existing system (if available, from step 2) can be made. Regardless of whether or not an existing system exists, however, the model results still need to be reviewed for correctness. Sensitivity analysis can be used to determine what model factors have a significant impact on performance measures and, hence, need to be modelled carefully.
7. *Design experiments.* In this step, issues that need to be specified include the length of each run (in time units) and the number of independent simulation runs needed using different random numbers.
8. *Make production runs.* This is the step when the simulation model is run to produce output data, which will be used in step 9.
9. *Analyse output data.* At this stage, output data is analysed for further use in the decision-making process in step 10.
10. *Document, present, and use results.* Document the assumptions used in step 2, the computer program and the study's results, for use in the current and future projects. To present the study's results, animation can be used to communicate the model to people who are not familiar with all the model details. The process of model building and validation can also be discussed to promote credibility. It should be noted that the results can be used in the decision-making process if they are both valid and credible.

3.2.5 Comparing programming languages and simulation packages

To build a simulation model, one can use a general-purpose programming language, such as *C* or *C++*, or a simulation package, such as *Pertmaster*, *Simula,* etc. Unlike a general-purpose programming language, a simulation package is a program specifically intended for use on simulation, which makes it easy to extend and modify a model using built-in features for problem resolution. Law and Kelton (2000) identified a number of advantages of using each of these two, as will be described below.

The advantages of using a general-purpose programming language for building simulation models, include:

- *Most modelers already know a programming language.* This is, however, often not the case with a simulation package.
- *A simulation model efficiently written in C or C++ may require less execution time than a model developed in a simulation package.* This is because the former can be tailored closely to a particular application, while a simulation package is designed to address a wide variety of systems with one set of modeling constructs. The availability of inexpensive, high-speed computers, however, has made this consideration become less important.
- *Programming languages may allow greater programming flexibility than certain simulation packages.*
- *Software cost is generally lower, but total project cost can be expensive.*

The following are some advantages of using a simulation package rather than a general-purpose programming language.

- *Simulation packages automatically provide most of the features needed to build a simulation model.* A significant decrease in programming time and a reduction in the total cost is achieved.
- *Simulation packages provide a natural framework for simulation modelling.* Their basic modelling constructs are more similar to simulation than are those in a general-purpose programming language like C.
- *Simulation models are generally easier to modify and maintain when written in a simulation package.*
- *They provide better error detection because many potential types of errors are checked for automatically.* Fewer modeling constructs need to be included in the model, in comparison with the use of a general-purpose programming language, hence the chance of making an error is smaller.

3.2.6 Recent uses of simulation in research in the construction industry

The fast development of computers has enabled a wide use of simulation in many disciplines, including the construction industry. Some simulation packages are known in the construction industry; either general purpose simulation packages (e.g., *GPSS,*

Simula, Simscript, Slam II, and Gasp) or simulation packages specially developed for the construction industry (e.g. *Cyclone, Resque, Siren, Steps and Picasso*) (Ammar and Mohieldin, 2002). In the construction supply chain, efforts have been made to use simulation, e.g. Arbulu and Tommelein (2002a) simulated the lead time of pipe supports used in power plants using a software package called *Stroboscope,* and Sobotka (2000) made use of *GPSS World*^{TM} to simulate logistics re-engineering in a construction company. For the research reported in this thesis, a piece of monte carlo project risk management software called *Pertmaster Risk Expert*^{TM} *v7.82* was used for the purpose of the simulation, and this will be discussed in section 5.2.

Monte carlo method is a simulation technique which has been used in many areas, including project management, where monte carlo simulation of project networks has now become a standard project-modelling technique (Williams, 2004). This technique allows complex combinations of uncertainties to be modelled to show their impact on a project. It is basically a mathematical method used to approximate the distribution of potential outputs based on probabilistic inputs. The inputs for the simulation can be task duration, cost, start and finish date, etc. Each iteration in the simulation is generated by randomly pulling a sample value for each input variable from its defined probability distribution using random numbers.

The sample values of the probability distribution are then used to calculate the desired outputs, such as total project duration, total project cost, critical paths, etc. This procedure is repeated until the desired level of accuracy is achieved. The probability distributions used can be obtained either from historical data (empirical), or from using a theoretical probability distribution, such as uniform, normal, triangular, beta, etc.

3.3 Research methods adopted in the thesis

To achieve the aims and objectives of this research, the research methods adopted comprised preliminary investigations, a main survey and the development of simulation models, as shown by figure 3-3. The preliminary investigations were designed to gain a a first-hand appreciation of supply chain management practice in the construction industry, which was carried out in two stages. First, semi-structured interviews were conducted with members of the construction industry to identify concerns and uncover important issues affecting supply chains in construction. Second, regular visits were made to two medium-sized building projects over a period of 6 months to understand the supply chain management practice in construction in a real life situation and its impact on the project. The main survey that followed was intended to collect data required for developing simulation models. Questionnaires were used for this survey to obtain a wider response from practitioners in the construction industry and were developed using the inputs obtained from the literature review and the preliminary investigations, particularly from the regular visits where many examples of supply chain delays were obtained. The simulation models basically consisted of a generic CPM network of a typical medium-sized building project, which was obtained from one of the projects visited, and supply chain delays, which were obtained from the main survey. This simulation allowed

different supply chain management practices and their impact on project performance to be examined. The next sections will explains the research methods in more detail, with an exception of the development of simulation models, which will be discussed separately in chapter V. The results of the preliminary investigations and the main survey will be presented and discussed in chapter IV.

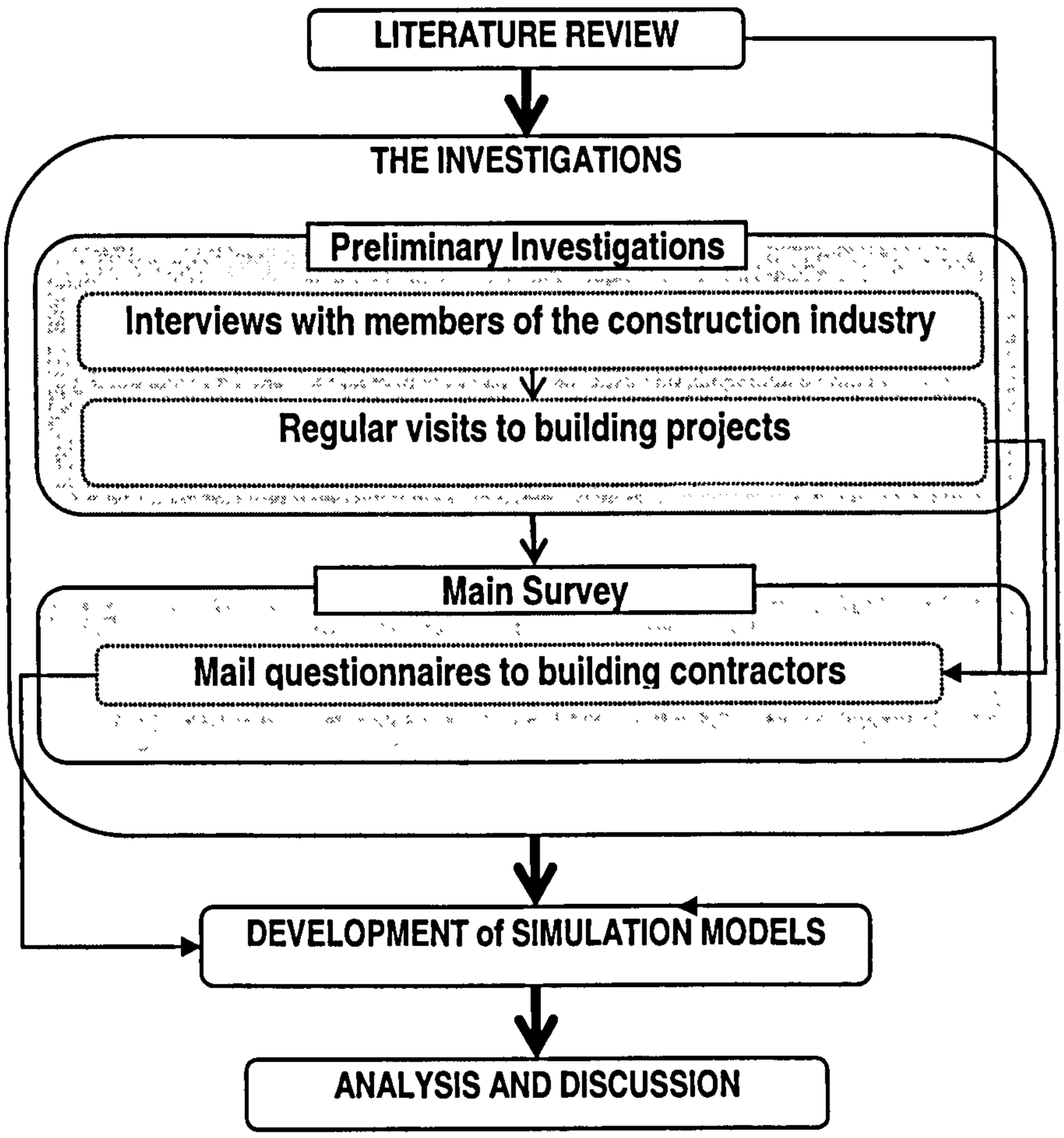


Figure 3-3 Research methods adopted

3.3.1 Preliminary Investigations

3.3.1.1 Interviews with members of the construction industry

As mentioned previously, the aims of this part of the work were to identify concerns and uncover important issues affecting supply chains in construction. To achieve these aims, semi-structured interviews were carried out with relevant organisations, such as contractors, subcontractors and suppliers, who had been in the construction industry for many years. To obtain valuable lessons, the companies chosen were well-established companies with good reputations. It was believed that they could offer

useful knowledge from a practical perspective, which might not be available in the literature.

3.3.1.2 Regular visits to construction projects

In order to gain a thorough understanding of supply chain management practice on construction sites, regular visits were planned to two construction projects over a period of 6 months. Through the regular visits, it was expected that the learning process would be achieved by immersion in the detail and daily activities on the projects.

A. The criteria for the projects to be visited

The criteria for the construction projects to be visited were adapted from O'Brien (1997), as follows:

1. The project should be relatively small to allow the researcher to identify and understand the major influences of SCM on site performance.
2. The project should be a common project which does not need special construction techniques or fabrication so that it can be generalized beyond the case.
3. Data regarding SCM and project performance should be accessible to the researcher.

School buildings or similar projects would best satisfy these criteria, as this type of project is normally medium-sized and not too complicated, allowing supply chain management practice and its major impact on the projects to be identified and more easily understood. For reasons of practicality and time limitation, the construction sites chosen should be in the Tyne and Wear area.

B. Collecting data from construction sites

To be able to keep up with the dynamic of the projects, site visits were planned to be made once a week, or more frequently, if necessary. Each visit was to last for approximately two or three hours and would ideally start as soon as the project had started and finish when the project was finished or when it was considered that there was no more to learn.

The purpose of the site visits was to learn about and observe supply chain management practice on a construction site and understand how it can impact on project performance. This was achieved by conducting observations and interviews on site. Observation included observing activities or incidents on site and making a record of them and also by examining the site documents, such as site diaries, project reports, minutes of meetings, etc. Interviews were mainly conducted with the site manager as he is the person who has the responsibility for managing the project, and was considered to have the best understanding of the construction process. However, other relevant persons who might be met on site, such as quantity surveyors, contract managers or subcontractors were also be interviewed.

3.3.2 Main Survey

As mentioned previously, the main survey was intended to gather data to permit the development of simulation models. To obtain a wide response, the main survey was conducted by distributing questionnaires via mail to target respondents in the United Kingdom. The questionnaire was developed using the inputs obtained from the literature review and the preliminary investigations. The detailed process of developing the questionnaire will be explained in section 4.2.1.

3.3.2.1 The respondents

The target respondents were mainly site managers who had experience in building school projects or similar building projects. Site managers were considered to be the best persons to answer the questions in the main survey as they have comprehensive knowledge about the general practice of the projects they are responsible for. However, responses from non site managers (e.g. quantity surveyor, director, managing director, etc) were also taken into account providing they had enough experience in the construction industry. These respondents were chosen from a list of 150 leading main contractors in the United Kingdom as listed in NCE Contractor File, July 2005. From the list, a selection of 92 companies which were involved in building projects was identified.

3.3.2.2 Sending the questionnaires

To increase the response rate of mail-based questionnaires, some techniques can be applied, e.g. personalization of cover letter, provision of self-stamped return envelope and deadline. Dillman (1991) has shown that personalizing letters addressed to specific individuals can increase the response rates of postal mail surveys. Provision of self-stamped return envelopes also increases the possibility of getting a higher response rate (Yammarino et al., 1991). A deadline was also mentioned in the cover letter to remind and encourage the respondents to complete the questionnaires within the time limit. All of the above were employed for this survey and to further increase the response rate, reminder calls or emails followed after 3 or 4 weeks.

3.4 Triangulation

Triangulation refers to the use of different research approaches, methods and techniques in the same study which is intended to overcome the potential bias and sterility of a single method approach (Collis and Hussey, 2003). The use of triangulation leads to greater validity and reliability than a single methodological approach (Denzin, 1970). According to Easterby-Smith *et al.* (1991) there are four types of triangulation, i.e. data triangulation, investigator triangulation, methodological triangulation and triangulation of theories as summarised in table 3-5 below.

Table 3-5 Four types triangulation (developed from Easterby-Smith *et al.* (1991))

Triangulation	Description
Data triangulation	Data is collected at different time or from different sources
Investigator triangulation	Different researchers collect the data independently on the same phenomenon and compare the results
Methodological triangulation	Both quantitative and qualitative methods of data collection are used
Triangulation of theories	The use of one theory of one discipline to explain a phenomenon in another discipline

The research reported in this thesis meets the descriptions of data triangulation and methodological triangulation, as data was collected from different construction sites, and both quantitative and qualitative methods of data collection and analysis were used. Collecting data from different construction sites widens, strengthens, and enriches the range of the data being collected. It was also expected that the bias which might exist from collecting data solely from one site could be avoided, and the level of generalisability of the data would increase. As for methodological triangulation, quantitative and qualitative methods of data collection were used in different stages of the investigation. In the preliminary investigations, the interviews with members of the construction industry provided more qualitative data, while the regular visits to sites provided both quantitative and qualitative data. In the main survey, more quantitative data were obtained from the respondents. In addition, the use of the other method, i.e. simulation, which was developed to represent the real-life situation on a contruction site as well as to quantify the impact of supply chains on the project, was also expected to increase the robustness of this research.

Chapter 4
The Investigations

This chapter explains in detail the investigations carried out for this research, namely the preliminary investigations and the main survey. This chapter has two main sections as follows:

4.1 Preliminary investigations: this section describes the preliminary investigations, which were conducted in two stages: interviews with members of the construction industry and regular visits to construction projects. Each of these preliminary investigations is described in detail, followed by a discussion of the lessons learnt from it.

4.2 The main survey: Here, how the main survey was designed and conducted is explained, followed by the presentation of the results.

4.1 Preliminary Investigations

4.1.1 Interviews with members of the construction industry

As previously mentioned, the aims of the interviews were to identify concerns and uncover important issues affecting supply chains in construction. They were carried out in March 2004 with 2 contractors, 1 subcontractor and 1 supplier in the United Kingdom, all of whom had been involved in the construction industry for many years.

4.1.1.1 The companies and the interviewees

The two contractors interviewed for this part of the work were; a civil engineering division of contractor 'A' and a building contractor, 'B'. The subcontractor, 'C', was specialised in earth moving, and the supplier, 'D', mainly supplied aggregates to civil engineering and building projects. They were all located in the North East of England.

To give an idea of the size of the organisations, A's project budgets ranged from £100,000 to £10 million, with typical contracts were approximately £1.5-2 million. B's project budgets ranged from £150,000 to £25 million. C's volume of sales in 2003 was £25 million and although no financial figures were available for D, one of its quaries supplied 850 thousand tonnes of aggregate in 2003.

The interviewees of these companies were the business development manager (company A), project coordinator (company B), director (company C), and plant

manager (company D). All held important positions within their companies and had long experience and a good understanding of the industry.

4.1.1.2 The questions

The question areas for the main contractor, subcontractor and supplier covered similar ground, as shown in table 4-1 below. In this way, the answers from these different organisations could be easily compared. Some specific questions, however, were ommited or added, as they applied to one type of organisation, but not to others. As this was a part of preliminary investigations, which aimed to gain insights from the industry, at this point, the questions were wide-ranging and were meant to capture as much information as possible. The list of specific questions for each of these organisations can be found in appendices A1, A2 and A3.

Table 4-1 Question areas for main contractor, subcontractor and supplier

Main Contractor	Subcontractor	Supplier
A. Project characteristics B. Subcontractors/suppliers selection C. Contract D. Site Performance E. Customer satisfaction F. Technical operation G. Performance assessment of subcontractors/suppliers H. Incentives for subcontractors/suppliers I. Disputes, Partnering J. Risk and Uncertainties K. IT/internet L. Main Problems M. Degree of Involvement	A. Company's characteristics B. Obtaining work C. Your suppliers D. Site Performance E. Customer satisfaction F. Performance assessment G. Incentives from clients/subcontractors/for suppliers H. Disputes, I. Partnering J. Risk and Uncertainties K. IT/internet L. Main Problems M. Degree of Involvement	A. Supplier's characteristics B. Contract C. Performance D. Customer satisfaction E. Competitive advantage F. Technical operation G. Flexibility and responsiveness H. Disputes I. Partnering J. Risk and Uncertainties K. Purchase order L. IT/internet M. Main problem N. Consumer's behaviour

4.1.1.3 Lessons learnt from the interviews with members of the construction industry

To be able to compare, analyse and learn from the results of the interviews more easily, the responses were tabulated in a matrix form, which can be found in appendix A4. Some interesting points were learnt, as will be discussed below.

1. Contractor 'A' reported that the number of subcontractors and suppliers involved in his civil engineering projects was 10 and 15, respectively, while contractor 'B' reported the typical number of subcontractors involved in his building projects was 20-30. Although these figures were likely to vary, depending on the projects' size and complexity, and might not be true for all civil engineering and building projects, they could indicate that the number of subcontractors and suppliers in building projects was likely to be greater than in civil engineering projects. This make sense as the types of work and materials in building projects are typically more diverse than those in civil engineering projects. An increased number of

suppliers and subcontractors in a project obviously contributes towards more complex supply chains. Such complexity can also be illustrated by the fact that at the time of the interview, subcontractor 'C' had 150 live contracts to fulfil, and supplier 'D' had to supply materials to 40 projects.

2. It was also reported that the typical duration of civil engineering projects of contractor 'A' was 4-6 months, which was less than the typical duration of building projects of contractor 'B' of 10-12 months. Again, although these figures might not represent all civil engineering and building projects, and were likely to vary, depending on the projects' size and complexity, this longer duration for building projects may be an indication of the more complex supply chains in building projects.

3. The main contractors had a list of subcontractors and suppliers in their databases they had known for years. Typically, local subcontractors and suppliers were preferred to national subcontractors due to their closer location and more competitive price. However, national subcontractors and suppliers might still be used for specialised work or certain materials which could not be procured locally. Price was still the most important criterion for the selection of subcontractors and suppliers, alongside other factors like finance, health and safety, quality, management, and experience. The subcontractor and the supplier mentioned that most of their work was obtained by competitive tender and only a few jobs by negotiation. This could be seen as an indication of the continuing use of competition in the construction industry.

4. Regarding contracts, these organisations had their own standard form of contract to suit their needs. While subcontracting or outsourcing work was a normal practice for the main contractors, this was not the case for the subcontractor and supplier.

5. For contractors, site performance was monitored periodically on a weekly basis. A set of parameters was used, including time, cost, quality and health and safety. Supplier 'D' also applied this kind of parameter to monitor the performance of its quarry. Benchmarking of performance was carried out internally. External benchmarking against the industry or other companies was seen as difficult to carry out and not really necessary.

6. The contractors assessed their subcontractors' and suppliers' performance after the end of each contract or periodically. This was done in the end of contract review meeting or by distributing questionnaires to them. Contractor 'A' reported that besides assessing subcontractors' and suppliers' performance, he also asked them to give feedback. From this, it can be seen that performance assessment can be done top-down (from a contractor to its subcontractors/suppliers) or bottom-up (suppliers/subcontractors to a contractor). This process was seen as very useful as one organisation can get feedback from other organisations along the supply chain, allowing continuous improvement to be achieved.

7. Contractors and the supplier were all aware of customer satisfaction. Apart from subcontractor 'C', all organisations mentioned that they measured their customers' satisfaction level. This was done either through questionnaires or direct contacts. Although subcontractor 'C' did not measure his customers' satisfaction, he argued that the customers would tell him if things were going wrong. The effort to satisfy customers, however, sometimes has to be

compromised with the company's limited capacity to fulfil orders. Supplier 'C' admitted that sometimes it could not fulfil customers' orders on particular materials and might suggest alternative materials instead.

8. Both contractors 'A' and 'B' stated that bulk orders of materials with delivery schedules were common practice. These materials were sent directly to the construction site to avoid stockpiling and double handling. Thorough checks of the incoming materials on site would be done to ensure they met the required specifications. Materials which did not meet the requirement would be rejected. They were mainly natural products, such as timber, or raw materials, such as aggregates. Manufactured products, such as pipes, piles, and bricks, normally did not have such a problem. Late delivery of materials by a supplier was said to be not unusual, and might cause a considerable impact on the project. This was also the case for late delivery of work by subcontractors. Penalties might apply for large organisations, but were not commonly used for small subcontractors and suppliers.

9. The main contractors 'A' and 'B', mentioned that they might receive incentives from their clients to encourage good performance. Contractor 'A' stated that he was sometimes rewarded for savings made, which was also known as a target cost contract. Contractor 'B' added that this incentive from a client could be in a proportion of 50:50 or 40:60 (i.e. 40% of the saving made is for the client, and 60% of the saving made is for the contractor). This incentive from the client, however, was not likely to be passed down to their subcontractors/suppliers. Subcontractor 'C' stated that he never received such incentives, and argued that repeat business was seen as a kind of incentive from his clients (contractors) when they were satisfied with the previous work.

10. Disputes with clients were perceived to happen frequently. Common areas of disputes were identified in the areas of the quality of materials and workmanship, deliveries, costs (e.g. disagreement of price, additional cost due to exceptional adverse weather, cost of work acceleration due to late delivery/completion), etc. Negotiation with a no-blame scenario was the preferred way to resolve these problems. It was very rare to bring these problems to adjudication, arbitration or even court, since it might be costly and take a long time. Subcontractor 'C' reported he had only had three major claims in the last 22 years.

11. Building long term partnerships was seen as an important issue. In fact, there were examples where contractor 'A' and subcontractor 'C' had secured jobs with their clients through a multi-year partnership for 3 and 5 years, respectively. Partnerships were also established with downstream organisations. This was indicated by contractors' regular repeat busines with their key suppliers/subcontractors, which counted for more than 75% of the total number of transactions. The contractors mentioned that early involvement in the design stage was one of the main advantages of this partnership. Being involved in the design stage allows them to suggest best alternatives to the client, which in turn could reduce project costs, duration and potential conflicts between contractors and client/designers. This early involvement also means that the contractors could get inputs from downstream organisations, i.e. the suppliers or subcontractors, regarding alternative materials or specialised work.

12. Use of the internet to communicate between site and office and their supply chains was still limited. It had not been fully developed in their systems yet. The common tools of communication they used were phones and faxes.

13. To identify the main problems in the supply chain, the respondents were asked to name their main concerns, which could be associated with the materials supply or the subcontractor work. The main problems identified were as follows: delivery of materials, price and availability, lack of labour, subcontractor's adherence to the programme, communication, and limited time to respond and react. The last problem of lacking time to respond and react was especially reported by subcontractor 'C' and supplier 'D', when they were dealing with orders or inquiries from their clients (main contractors) and had to give a fast response.

As mentioned earlier, the questions in the interviews were wide-ranging, as they were intended to gain as much insight as possible from the industry. To narrow down the focus on the issue of how supply chain management impacts on project performance, the next investigation looks closer at the issues related to supply chain management in practice on two construction projects which were visited regularly over a period of time.

4.1.2 Regular visits to construction projects

In order to gain a thorough understanding of supply chain management practice on construction sites, regular visits were made to two construction projects over a period of 6 months, from mid November 2004 to the end of May 2005. Both projects were school building projects located in Tyne and Wear, UK and were carried out by different main contractors. It was learnt from the preliminary investigation that building projects would typically have more subcontractors and suppliers than civil engineering projects, as they have more specialised works to be done and need a wider range of materials. For these reasons, it was considered that more lessons could be gained by investigating supply chain issues on building projects rather than civil engineering sites. School building projects were chosen since this type of project is very common, normally medium-sized and not too complicated, allowing supply chain management practice and its major impact on the projects to be identified and more easily understood.

Through the regular visits, the learning process was achieved by a process of immersion in the projects. Useful lessons were obtained during the visits through direct observations, interviews, examination of project documents, attending project meetings, etc. From these visits, particular types of problems and delays on sites related to supply chain management practice were identified. These were useful examples from real life situations, and helped to reinforce the understanding of how problems with the supply chain can impact on project performance. Another spin-off from this study was that a specific CPM network from one of the projects visited was obtained and this became the basis of the generic CPM network later used in the simulation model. The following sections will describe the visits to each project. Because the characteristics of each of these projects were unique, the data available

or lessons learnt from them were sometimes exclusive and might not always be generalisable.

4.1.2.1 Project 1 (WBHS project)

A. Short description of the project

This was a school building project located in Newcastle upon Tyne, and was planned to start from 15 November 2004 and finish on 30 August 2005. The budget was approximately £2 million. The main contractor, 'X', was one of North Tyneside City Council partners. All the work in the project was subcontracted in packages, which meant that the subcontractors would do all the work and would, in turn, deal with their own suppliers and sub-subcontractors. The main contractor did not employ any workforce for this project and there were a total of 25 subcontractors involved in the project.

B. Lessons learnt from the WBHS project

The lessons learnt from this project cover issues such as: coordination meetings and information distribution, problems related to information flow, partnering and early involvement in the design, material delivery, and delays identified in the project. They will be discussed in more detail as follows;

1. Coordination meetings and information distribution

There were three kinds of regular meetings held on the WBHS project as shown by table 4-2. These regular meetings between the main contractor and client, design team, subcontractors, and suppliers allowed information to be communicated and managed along the supply chain. Information was passed from upstream organisations, such as client or design team to downstream organisations, such as subcontractors and suppliers, or *vice versa.* The main contractor was in the best strategic position to manage and pass this information from and to relevant organisations. Besides information, any problems that arose on the project could also be discussed in these meetings, so that solutions could be found as early as possible. These meetings also functioned as a way of keeping the project's progress on track, as the client could monitor the progress from the main contractor's report and the main contractor received progress reports from the subcontractors on a weekly basis.

Table 4-2 Meetings held in the WBHS project

Meeting	Held by	Attended by	Frequency
1. Design/information meeting	Contractor	- Contractor - Design team - Client (School)	2 weekly
2. Site meeting	Client	- Contractor - Design team - Client (Education services & School)	4 weekly
3. Independent meeting	Contractor	- Contractor - Suppliers - Subcontractors	weekly

2. Problems related to information flow

Before a particular activity in the project started, certain information was needed, such as drawings, specifications, setting out plans, permissions, etc. To record and manage this information, a form called *information required schedule* was used. It was found from this *information required schedule*, which was last updated on 16 May 2005, that there were 30 delays out of 39 information requests. In other words, 77% of information requests were received later than scheduled. Although the information was requested anywhere from 3 to 25 weeks before it was required, these delays ranged from 2 days to 20 weeks - counted from the date when the information was required. In addition, some of the information when provided was received incomplete. Figure 4-1 shows an example of an *information required schedule* for the project.

CONSTRUCTION PHASE
INFORMATION REQUIRED SCHEDULE

Form F19

Contract: [redacted] Contract No: [redacted] Page 1

Prepared by: D Wallas Date Issued: 08.10.04 Last Updated: 16.05.05

Prog Ref No	Description of Information Required	Requested From	Date Requested	Date Required	Date Received	Comments (References AI's letters etc)
1	Setting out Details with co-ordinates/finalised levels/new fence line	[redacted]	08.10.04	25.10.04	03.11.04	
2	Confirmation of benchmark/setting out point (Existing Sports hall Floor?)		08.10.04	25.10.04		Assumme existing sports hall floor
3	Existing services information including drainage		08.10.04	25.10.04	Part	Gas & electric only
4	Demolition layouts/proposals		08.10.04	25.10.04	03.11.04	
5	Ground floor plan 1:100		08.10.04	25.10.04	03.11.04	
6	NBS Specification		08.10.04	25.10.04		To be issued with packages
7	Foundations GA Concrete specifications Setting out Sections Reinforcent details & associated schedule		08.10.04	25.10.04		Preliminary copy 03.11.04 Schedule 04.11.04
8	Roof plan 1:100 (inc RWP + gutters)		08.10.04	01.11.04		Outstanding
9	Proposed Elevations		08.10.04	01.11.04	03.11.04	
10	1:50 longitudinal/cross sections		08.10.04	01.11.04	03.11.04	
11	Drainage layout with pipe diameters 1:100 Int. & Ext. (incl. Setting out)		08.10.04	01.11.04	03.11.04	
12	Manhole schedule with cover and invert levels		08.10.04	01.11.04	02.12.04	
13	Mechanical & Electrical Drawings & specifications Details of new incoming services		08.10.04	06.11.04	10.11.04	

Distribution:

Figure 4-1 Sample of *information required schedule*

There was also an example of a problem with distribution of information. A subcontractor responsible for the ceiling work, had somehow bypassed the main contractor by getting a drawing directly from the designer and had started to order related materials and did some work without the main contractor's instruction. At this time, the main contractor had not had a copy of this drawing and it was found later that the design had been changed. As a result, the materials ordered and some work that had already been done was of no use. The main contractor insisted he was not responsible for any costs resulting from this, since this subcontractor had done his job without following the proper procedure. As a result, the subcontractor had to be responsible for the rework and any costs incurred.

3. Partnering and early involvement in the design

The main contractor 'X' had been selected as one of the three partners of the client, North Tyneside City Council, since early 2004 and this partnership was to last for 5 years. The procurement system in this project was fixed price plus a percentage profit for the contractor. An open book financial system was adopted. Any savings or overruns from the project would be shared 50-50 between the contractor and client, hence there would be no liquidated damages.

The main contractor was also involved in the early design of this project to give input from its professional practical experience. This could benefit the project as it might improve the buildability and could also reduce the costs of the project.

4. Material deliveries

For safety reasons, there was a policy that the materials for the project had to be delivered at certain times outside the following times; 08.00 - 09.30, 11.00 - 11.35, 11.30 - 13.45, and 15.30 – 16.00. These were times when students arrived at the schools, had breaktimes and left school. Although this policy had been made known to subcontractors, nevertheless, there were some occasions when materials were delivered during these inapproriate times. The main contractor issued a formal complaint to the related organisations for any infringement of this policy.

5. Delays identified in the project

Table 4-3 below shows the delays identified in this project during the visits. They were mainly identified from the site diary. It can be seen that approximately 70% of the delays were caused by the effects of the weather. The other 30% were related to subcontractor's work, material delivery and labour. In other words, these 30% delays were related to supply chain issues. Unlike the weather delays, the hours lost due to these delays were not really known. This suggests that although their impact on the project was obvious, it was not always easy to quantify them.

Table 4-3 Delays identified from the WBHS project

Date	Delays	Impact	Types of delays
15.11.04	Too windy to erect fences	-	Weather
15.12.04	Poor progress of NML Non delivery times	-	SC issues (workflow & material flow)

Date	Delays	Impact	Types of delays
22.12.04	Not enough men on site	-	SC issues (labour)
10.01.05	Poor progress of NML	-	SC issues (workflow)
14.01.05	8-11am NML stood waiting for stilt saw , and left site 1 pm Reo could have been placed in foundation to stores plant	-	SC issue (equipment)
17.01.05	Block/bricks/mortar delivered, but unable to commence due to NML progress	-	SC issue (workflow)
27.01.05	Delay in starting ACL	-	Cost/budged issues
21.02.05	Hazardous condition i.e. lying snow Subcontractors were sent home at 10am	-	Weather
21.02.05	Adverse weather	360 bricklaying hours lost	Weather
21.02.05	Lying snow	8 hours time loss	Weather
22.02.05	No brickwork due to temp - 2 °C	8 hours time loss	Weather
23.02.05	Drizzle, low temperature 2°C	8 hours time loss	Weather
24.02.05	Drizzle, low temperature 5°C	4 hours time loss	Weather
28.02.05	Delay bricklayers work, low temp	6 hours time loss	Weather
01.03.05	Delay bricklayers work Little progress due to temp	6 hours time loss	Weather
02.03.05	Snow on the ground/cold/snow drizzle	4 hours time loss	Weather
03.03.05	Snow on the ground/cold/snow drizzle	2 hours bricklaying	Weather
22.03.05	Cloudy/heavy showers	4 hours	Weather
06.04.05	Roofer unable to work due to weather Heavy rain	4 hours time loss	Weather
14.04.05	Roofer unable to work due to weather Heavy rain	4 hours time loss	Weather
15.04.05	Roofer unable to work due to weather Heavy rain JFR left site, no production due to rain	7 hours time loss	Weather
18.04.05	Roofer unable to work due to weather Heavy rain JFR left site, no production due to rain	7 hours time loss	Weather

Source: Site diary

Of the delays related to supply chain issues, most of them were associated with subcontrator's work. It can be seen that according to the main contractor's record, most of these delays were due to poor progress of the subcontractors. There were some occasions when a subcontractor could not start his work on time or had to stop in the middle of his work, as he had to wait for the other subcontractors to finish their work, or the site was not ready yet. In such cases, the main contractor usually resequenced the work whenever possible to avoid further delays on the project.

It should be noted that the fact that there were only a few types of delay in this project could be an indication that the process was going well. However, it could also mean that there were other delays which were not identified at the main contractor level. As all work was subcontracted, many delays which could have occurred could have been dealt with at subcontractor level, and therefore might have not been identified and recorded properly by the main contractor.

4.1.2.2 Project 2 (ASC project)

A. Short description of the project

This was a refurbishment college building project located in West Denton, Newcastle upon Tyne, carried out by 'Y', as the main contractor. The allocated budget was approximately £2.5 million. This project was planned to start from November 2004 and finish in July 2005. Approximately 80% of the work was subcontracted. There were 34 subcontractors and 19 suppliers involved in this project. Some of the subcontractors were nominated by the client.

B. Lessons learnt from ASC project

1. Coordination meetings

There were three kinds of regular meetings held on the ASC project as shown by table 4-4 below. As in the WBHS project, these meetings can be seen as one way of communicating and passing information along the the supply chain from upstream organisations to downstream organisations, or *vice versa.* In addition, they also function as a means to discuss problems and find solutions, as well as keeping the project on track.

Table 4-4 Coordination meetings held in the ASC project

Meeting	Attended by	Frequency
1. Progress meeting	- Contractor - Architect - Client (School)	2 weekly
2. Subcontractors meeting	- Contractor - Subcontarctor	2 weekly
3. Internal review meeting	- Contract manager - QS - Site manager	monthly

2. Procuring materials and delivery times

Figure 4-2 below shows the normal routes of procuring materials for this project. The site manager sends requisition forms to the Buyer in the office. The Buyer sends the purchase order to the suppliers and sends the copy of the purchase order back to the site. The suppliers respond to the buyer and send the materials directly to the site. The materials could be delivered all at once or when the site needs them, however, some materials which are needed urgently can be ordered directly from the suppliers by the site manager.

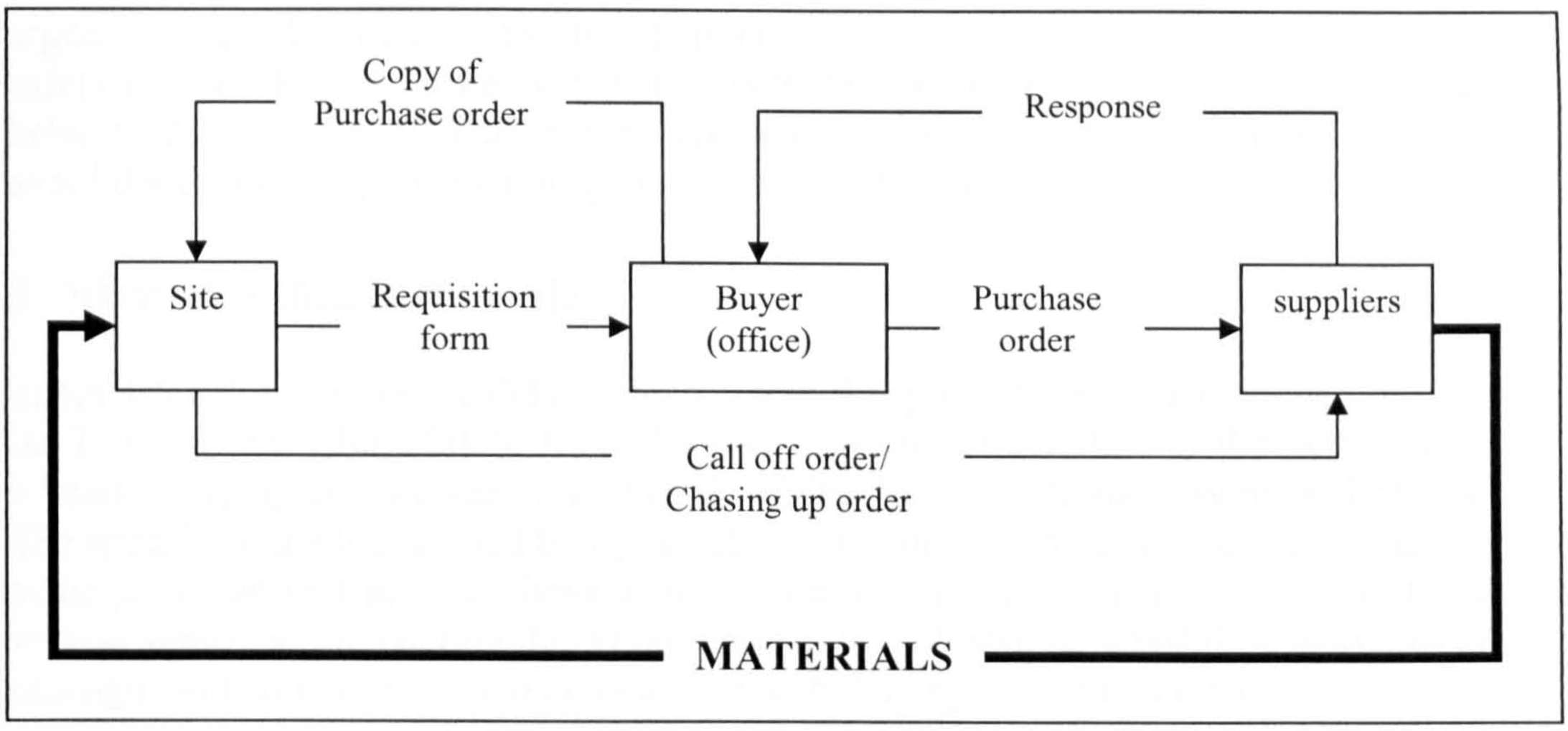


Figure 4-2 Routes of procuring materials of ASC project

To be able to get the materials at the right time, the lead time in procuring materials was seen as an important factor to be considered. The lead time is the amount of time needed from placing the order to getting the materials delivered to site. Some materials may be generally available and easy to get straight away from the merchants within the same day, but some others may have weeks of lead time to procure, especially for specially designed materials. Figure 4-3 below shows some examples of lead times of materials in the ASC project which ranged from 1 day to 8 weeks.

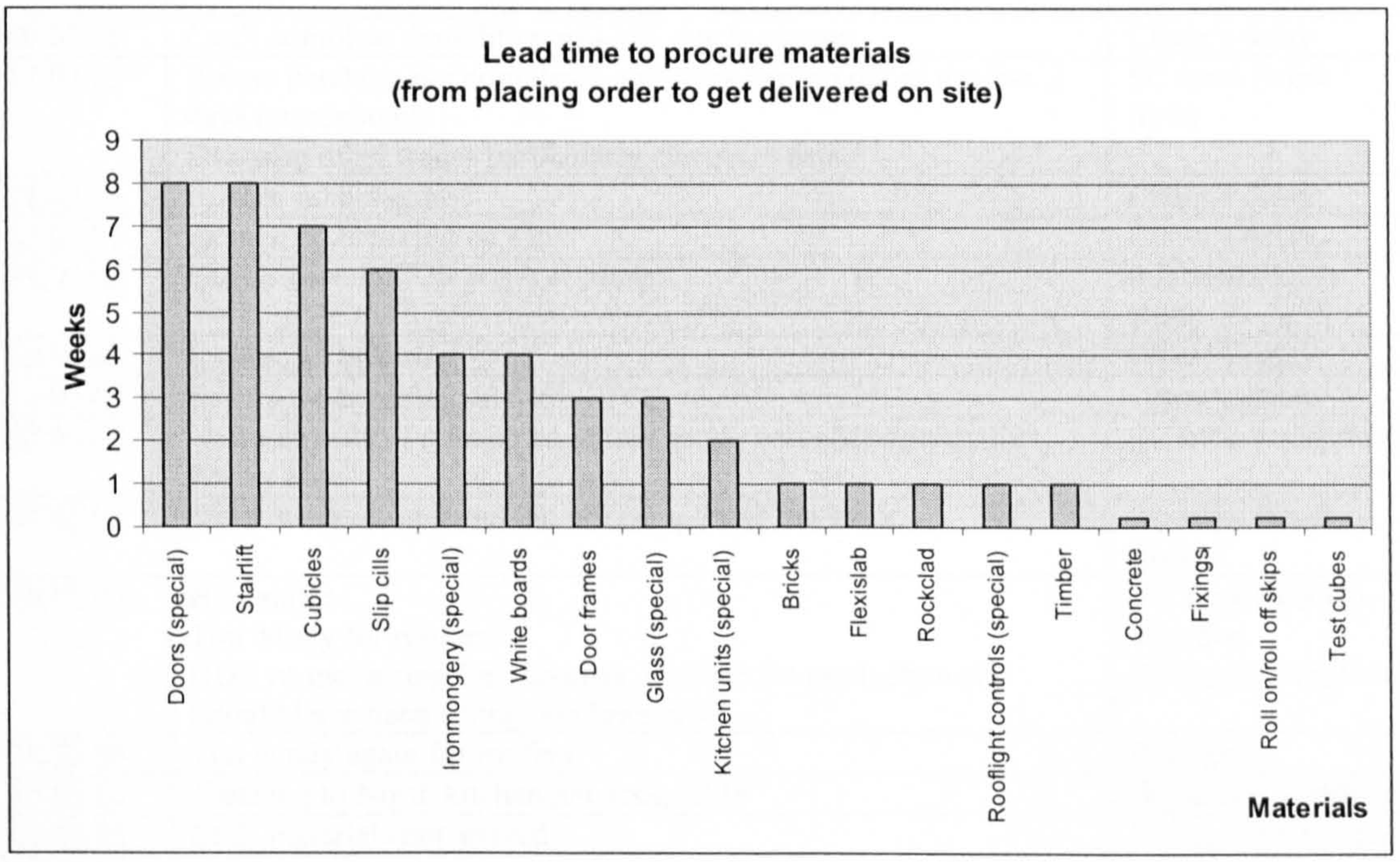


Figure 4-3 Lead times of procuring materials

In this project, a *materials required schedule* was not available. The site manager simply relied on the programme - a simple bar chart without links, and based on his 30 years experience he knew when to place an order for materials. He argued that due to the scale of the project, a *material required schedule* was not needed. The same

argument was also offered by the contract manager. As in the WBHS project, for safety reason, delivery times for materials were allowed only at certain times, i.e. between 09.00 to 14.30. This was considered the best time for material deliveries to avoid disruptions to pupils coming to and leaving the school.

3. Delays identified in the project

Table 4-5 below shows the delays identified in this project from 1 November 2004 to the last visit on 8 June 2005. It can be seen that more than 70% of the delays were related to supply chain issues, and the remaining 30% were caused by natural causes. The specific hours lost caused by these delays were not recorded in the diary. The site manager stated that most of these delays affected non critical activities, hence, there was no significant impact on the whole project. In addition, re-scheduling activities or reassignment sources was also done to diminish the impact of these delays.

Table 4-5 Delays identified in the ASC project

Date	Delays	Types of delays
01.11.04	Asbestos survey	Client's delay
02.11.04	Insufficient labour on site	SC issue (Labour)
05.11.04	No labour available for demolition	SC issue (Labour)
07.12.04	Late information on roof lights and windows	Client's delay
20.12.04	No plasterers, boarders on ceiling fixing so boarding stopped	SC issue (Labour)
21.12.04	Plasterer on site but boarders taking off other job	SC issue (Labour)
19.01.05	Dumper and machine still on site but off hired HDR is poor	SC issue (plant) Subcontractor's work
09.02.05	Can't complete demolition of LNK due to alarms.	Client's delay
17.02.05	Plaster patching not completed and work carried out in the last 2 days unacceptable Delaying other trades particularly electric + data	SC issue (work flow)
21.02.05	Exams, no breaking	Client's delay
22.02.05	Exams, no breaking on Link	Client's delay
23.02.05	HDR is poor. DMK is at risk at present	Subcontractor's work
28.02.05	Exams, no breaking	Client's delay
01.03.05	Exams, no breaking on Link	Client's delay
02.03.05	No patchwork. To finish computer room, will not be ready for Friday now.	SC issue (workflow)
07.03.05	DMK worked weekend but not completing the work	SC issue (work flow)
16.03.05	No painter Too windy for roofers HDR re-measuring for windows. No date for production yet. Should have been fitting windows now.	SC issue (labour) Weather SC issue (workflow)
18.03.05	Too windy again for roofers	Weather
23.03.05	Cleaning to North kitchen not acceptable	SC issue (workflow)
05.04.05	LMF materials not arrived.	SC issue (materials)
07.04.05	Roofer gave up due to weather Windows short of no.2 screen	Weather SC issue (materials)
08.04.05	Too windy for roofer	Weather
14.04.05	External work lost due to rain	Weather
15.04.05	External work lost due to rain	Weather
18.04.05	External work lost due to rain	Weather
26.04.05	Roofer rained off	Weather
28.04.05	Plasterer left site again this afternoon	SC issue (labour)

Date	Delays	Types of delays
03.05.05	Roofers rained off (rain am, cloudy pm)	Weather
13.05.05	Windows still not complete, many outstanding item	SC issue (workflow)

Source: site diary

The delays related to SC issues, can be associated with labour, information from the client, subcontractor's work, equipment and materials. These delays will be discussed in more detail below:

a. Delays associated with labour

There are several examples above of delays when labour was either not available or there was not enough labour available. In this project, labourers, plasterers, and painters were some of the skills which caused delays. There was also an example when the plasterers took several days off from this project to finish work on another project, which could indicate that this particular skill was in high demand.

b. Delays associated with information/client

One of the first delays from the client was when the site was not ready, since an asbestos survey had to be carried out, which delayed the project by several days. There was also late information regarding the design and specifications of the roof lights and windows from the architect, as the client's representative. This caused delays in placing an order for the materials and hence delayed the work. This also happened with the kitchen, where the main contractor had to wait for about 2 months to obtain the client's decision to reuse the old kitchen or to buy a new one. Variations or extra work from the client also caused delay, for example, due to the extra work of installing a plasma screen, the ceiling work had to be stopped.

Another example of late information from the client concerned an exam scheduled for the college's students. As the site manager was not aware of this exam in advance, he did not put the exam period in the programme. As a consequence, and to avoid disturbance to the exam, the site manager had to reorder the sequence of some work and redistributed the labour to work away from the rooms used for the exams.

c. Delays associated with subcontractor's work

There were some notable disruptions due to subcontractor's poor performance. On some occasions, the poor progress of the subcontractors even caused disruption to other trades. There were some examples where they left the work incomplete and came back later to finish the work. For example, one of the subcontractors who was responsible for window intallation, put the window frames in place, then left them incomplete. They came back several days later, only to install handles, hinges, etc. The site manager said that although this way of working was extremely inefficient and put the work of other trades at risk, he understood that many of these subcontractors had other works to do in different projects. They had to stop their work for a while on one project to be able to finish the other jobs. Sometimes, they were allowed to work during the weekend to catch up with the schedulle. He

also argued that as long as this work was not on the critical path, he did not charge them for damages. There was, however, an example when the main contractor produced a note to one of the subcontractor due to his *"inability to progress works on site which have subsequently delayed other trades"*. In this case, this subcontractor was charged for any claims resulting from this delay.

d. Delays associated with plant

In this project, there was only one example which was related to plant or equipment. In this case, the plant was still on site although off hire. Although no specific delay resulted, the plant occupied some space which could otherwise have been used for other materials or activities.

e. Delays associated with materials

Although most materials arrived on time, some delays were identified in this project. They included late delivery of materials, missing items on delivery and damaged materials. Delay to the installation of windows and doors was one of the examples of a knock-on effect on the project, and in addition, some missing components of the windows also contributed to these delays. Although the late delivery of materials was normally caused by the suppliers, it could also happen due to late information from the client/architect, which resulted in delays in placing the orders. This was the case with the roof lights and windows as previously mentioned. There was also an example where a window glass was damaged on arrival on site due to careless handling by a worker, and it took several days to get a replacement. The main contractor did not penalise the suppliers for any of these delays.

This section has described the lessons learnt from the regular visits to the ASC project. This was a useful way to appreciate issues related to supply chain management in a real life situation on site, and the lessons learnt will be used for developing the questionnaire in the main survey, which will be discussed in the next section.

4.2 The Main Survey

The main survey was the last part of the investigation and was intended to gather data to be incorporated into the simulation model. To obtain a wide response, this main survey was carried out by distributing questionnaires to contractors specialised in building projects in the United Kingdom. The following sections describe the stages of developing and testing the questionnaire, and the results of the main survey.

4.2.1 Developing the questionnaire

The questionnaire was developed using the inputs obtained from the literature review and the preliminary investigations. The process of developing the questionnaire, as shown in figure 4-4 below, involved a number of steps. The first step was to list as

many types of delays on construction projects as could be found from the literature, as can be seen in appendix A5. Examples of delays learned from the preliminary investigations were also added to the list. These delays can be attributed to various aspects of a project, such as materials, financial, nature, site conditions, transportation, etc. They can also be seen from the perspective of who is responsible for the delays, e.g. contractors, client, suppliers, or subcontractors.

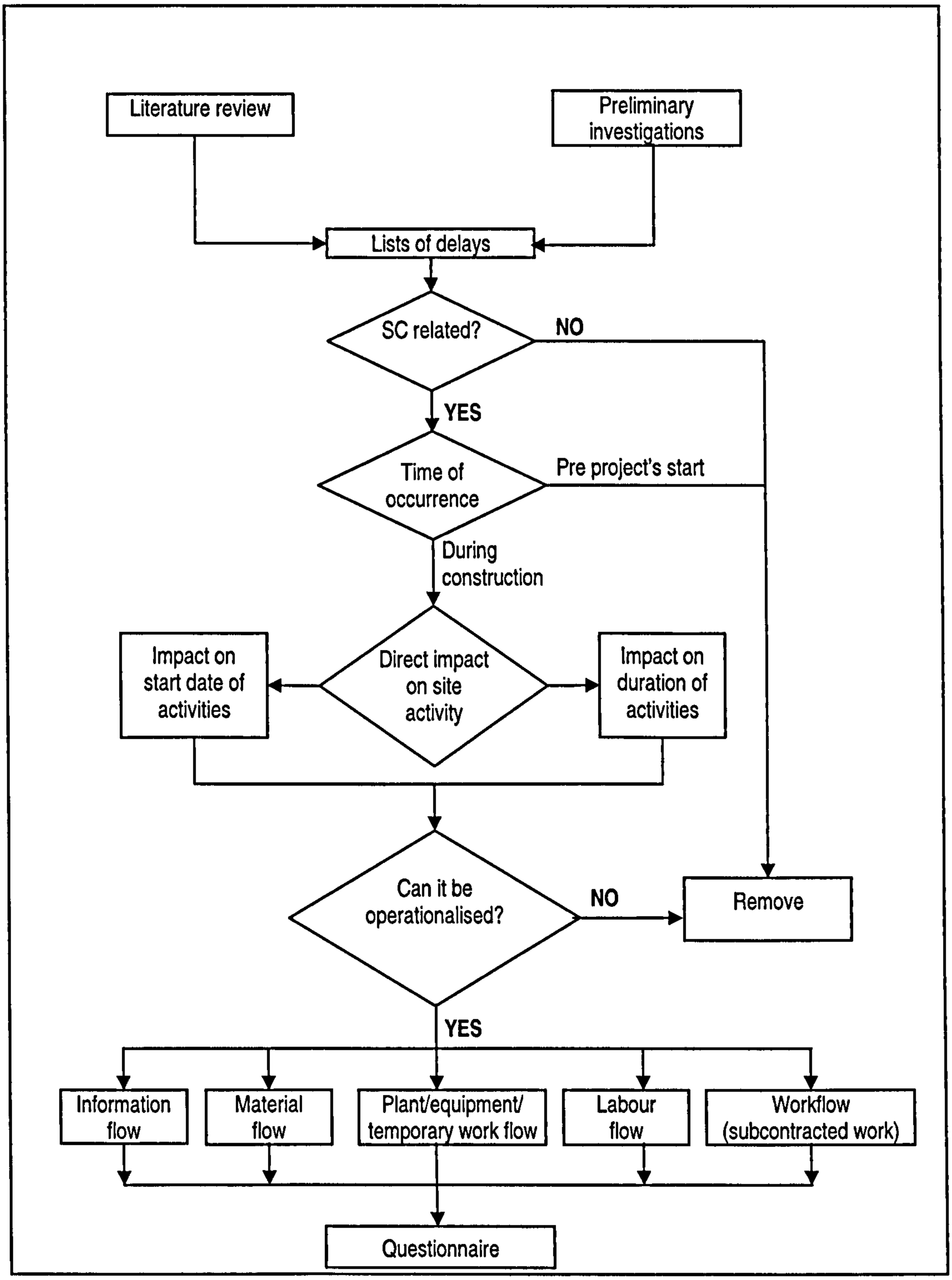


Figure 4-4 Steps of developing the questionnaire

In order to make the list simpler, clearer and to avoid confusion, it was necessary to remove some delays which overlapped and others that were duplicated. The simplified list can be found in appendix A6. It should be noted that not all the delays in this list were relevant to supply chain issues, and hence to simplify further, the next step was to select only delays which were related to supply chain issues and remove those which were not. This process of selection is also shown in appendix A6.

The remaining supply chain delays can be seen from the perspective of time of occurrence, as they may occur either before the project starts or during the construction period. However, the simulation model only deals with delays that occur during the construction period, hence delays which may occur before the project starts were not used. For delays that do occur during the construction period, they may happen before a particular activity starts, which may prevent it from starting on time, or during the project activity, which may extend the activity duration. To narrow down the focus, the next step was to identify which delays may impact on the start date of activities and which ones may impact on activity duration.

As mentioned previously, the questionnaire was intended to gather data for simulation, hence, the probability of an event occurring and its extent if it does occur were required. With regard to this requirement, the delays must be able to be operationalised, meaning that it must be possible to know the probability of an event occurring and also its extent if it does occur. However, not all the delays identified as related to supply chain issues on construction sites could be operationalised. For example, *poor material planning* is one of the causes of delays related to supply chain issues on a construction site. It is difficult to operationalise such issue, because it is very difficult to know the probability that *poor material planning* will occur or to know the extent of its impact when it does occur. Hence, this delay and the other delays which could not be operationalised were removed from the list. It should be noted that while these sort of delays were not separated and considered directly, they are actually already included, as they will be a proportion of other delays (e.g. poor material planning could be included in 'difficult in sourcing materials').

The remaining delays which could be operationalised were then classified based on the flows identified in the construction supply chains. They were categorised into five categories, i.e. information flow, material flow, equipment/plant/temporary work flow, labour flow, and workflow. Three of these flows are an adoption of the categorisation of construction supply chain types of Muya *et al.* (1999) who pointed out that there are three types of construction supply chain, i.e. the primary supply chain, the support chain and the human resource supply chain. The primary supply chain delivers the materials that are incorporated into the final construction product, for example, raw materials, components, sub assemblies and mechanical and electrical equipment. The support chain provides equipment, expertise and materials that facilitate construction, for example, falsework and framework, excavation supports, scaffolding, temporary works related to operation of equipment, site access. The human resource supply chain involves the supply of labour and the supervisory staff as inputs to the construction process. In other words, the construction supply chain involves the flows of materials, plant/equipment/temporary work and labour.

In addition to these three flows, the other delays can also be categorised into information flow and work flow. Delays in information flow include delays in obtaining permissions, specifications, drawing etc, while delays in work flow refer to delays due to subcontracted work. Table 4-6 below shows these five categories of the construction supply chain flows (column 1) and the questions developed for each flow category (column 2) .

Table 4-6 Categorisation of delays related to supply chain issues which can be operationalised

Construction supply chain flows	Questions to ask
(1)	(2)
Information flow	Activity affected by delays of information flows?
Material flow	Typical material to be delivered late + time buffer?
	Typical material delivered with the wrong specifications?
	Typical material delivered with insufficient quantity?
	Typical material delivered damage on arrival?
	Typical material difficult to obtain in the market?
Equipment/plant/ temporary work flow	Typical Equipment/plant /temporary work in shortage?
Labour flow	Typical skills in shortage during construction period?
Workflow (subcontracted works)	Typical work to be subcontracted?

The questionnaire was designed as semi-open, which gave the respondents a degree of freedom in answering the questions. Besides choosing the answers from the options available in the questionnaire, they were also allowed to answer by filling the blanks provided. The reason behind this was to obtain a broader coverage and feedback in comparison to a closed-type questionnaire which has a limited choice of answers.

To give the respondents a context to help them respond, it was stated that the questionnaire referred to a typical school or similar building project in the UK. In general, the questionnaire asked the respondents to identify specific examples of delays in the construction supply chain that were likely to occur on such a site, e.g. which materials would typically be delivered late, which subcontracted works would typically start late, etc. They were then asked to indicate, in percentage terms, how often these delays would occur, which represent the probability of occurrence, and to indicate the extent of the impact if they did occur. The extent of the impact was represented by 3 values, i.e. minimum, most likely and maximum, to define a distribution that could be used in the simulation. The following is a typical example of the questions in the questionnaire, "Which materials would typically be delivered later than the scheduled date?", "How often would this occur?", "When these delays did occur, please estimate their duration (minimum, most likely and maximum)." The complete questionnaire including the cover letter can be found in appendix A7.

4.2.2 Testing the questionnaire

To test whether questions in the questionnaire were clear and could be answered by respondents, the questionnaire was tested on 2 site managers from different companies. They had been in the construction industry for 15 and 38 years respectively and both had experience in building school projects, thus, they were

considered eminently eligible to test the pilot questionnaire. In general, they commented that the questions were reasonably clear and could be answered, although (as expected) not very easily. Some very minor changes in terms of wordings were proposed. All in all, the questionnaire was considered workable.

4.2.3 Results of the main survey

4.2.3.1 The responses

Of the 105 questionnaires distributed in early January 2006, a response rate of 22% was obtained. Although the targeted respondents were mainly site managers, the respondents who returned the questionnaires varied, as shown in figure 4-5. They were site managers (53%), project managers (30%), quantity surveyors (13%) and building managers (4%). In addition, most respondents indicated that they had been involved in the industry for a long time, with an average of 22 years. With such a profile of respondents, who were mainly site or project managers, and with such long experience of 22 years, it can be said that the information gathered was reasonably reliable, as they had been involved in many projects and had a good understanding of the industry.

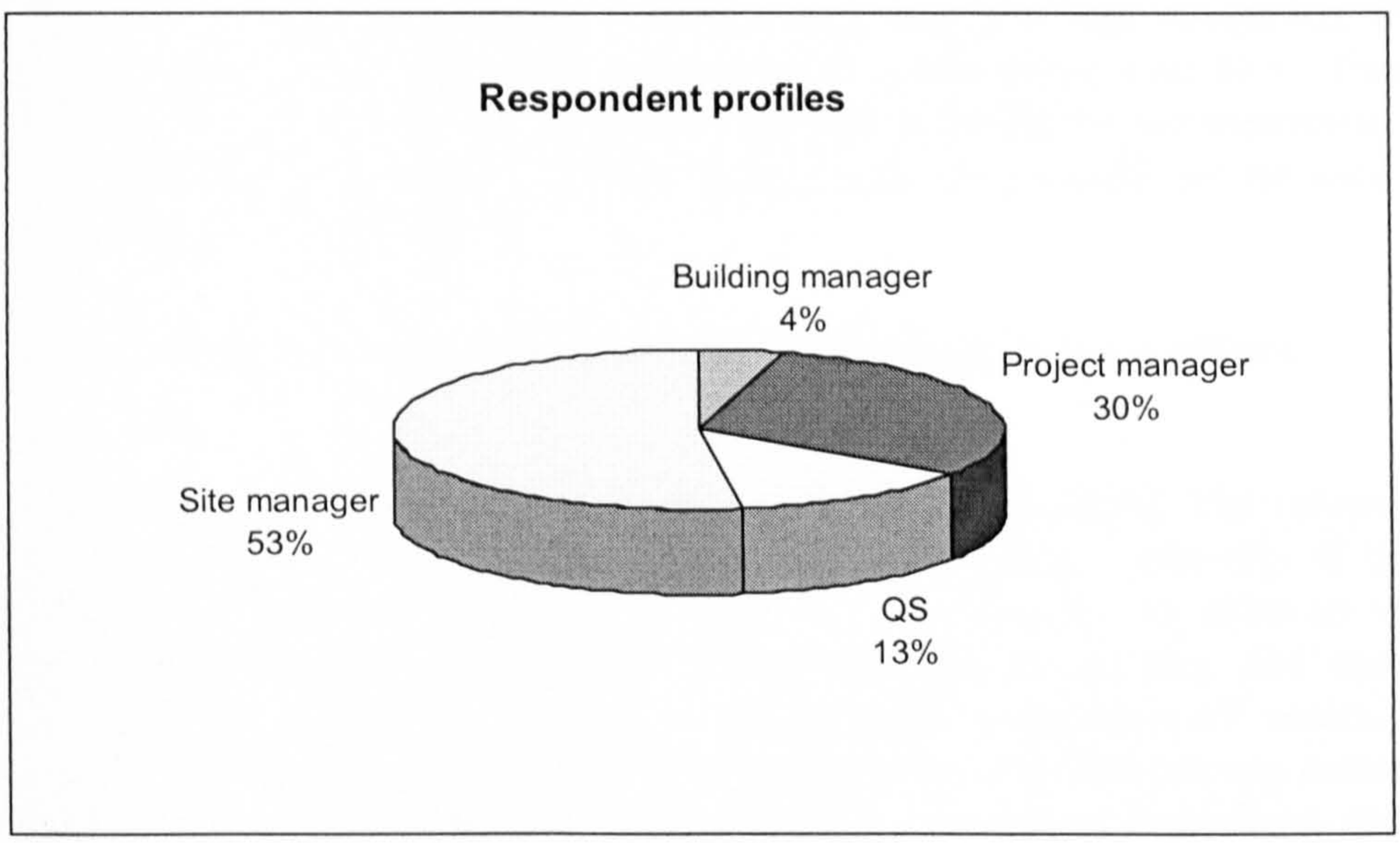


Figure 4-5 Profiles of respondents

4.2.3.2 Grouping and labelling similar data

To deal with the variety of feedback from the respondents regarding materials, activities, subcontracted works, etc, it was necessary to group those which were similar or overlapped. For example, respondents wrote down the following terms, "steel frame", "steel work", "structural steelwork", "steel erection", which actually refer to the same work. In another case, a respondent wrote down "groundwork and substructure", another respondent wrote down "substructure and drainage", others simply wrote "groundwork", "drainage" or "foundation". To simplify and make this data workable, the terms which actually refer to the same or a similar activity were

then grouped into one variable and given an appropriate label. In the first example mentioned above, a label of "structural steelwork" was used. The terms which overlap, as shown in the second example, were broken down and placed into the correct variables. In this case, three variables of "groundwork", "drainage" and "foundation" were used. This means that "groundwork and substructure" can be broken down into "groundwork" and "foundation", while "substructure and drainage" be broken down into "foundation" and "drainage". For each variable the mean of the frequencies and the mean extent of delays (minimum, most likely and maximum) as reported by each respondent to the survey was then used for the simulation.

4.2.3.3 Removing invalid data

Typical questions in the questionnaire asked the respondents to name activities or materials which might be affected by supply chain delays, indicate the probability (in percentage terms) that they would happen, and indicate the extent of them if they did happen. For example, the respondents were asked to name typical works to be subcontracted to specialist subcontractors. Later they were asked to indicate the probability that these subcontracted works would start later than the scheduled dates and how late they could be (min, most likely and max). One respondent indicated a typical area of work to be subcontracted and put a figure of 0% to indicate the probability that this subcontracted work would start later than scheduled. By putting 0%, he indicated that the subcontracted work would never start late. However, he then put 100, 130, 150 to indicate the minimum, most likely and maximum extent of delays. This kind of answer is not logical and, thus could not be used and was removed from the data set.

4.2.3.4 Mean as the representative of data set and the outliers

To represent the data set, the mean was used for each variable. The rationale behind this was that the mean can represent the data properly, especially if the data is normally distributed. However, the mean is very sensitive to extreme values. An extreme value can pull the mean in one direction or another and make it less representative of the data set and less useful as a measure of central tendency (Salkind, 2000). To provide a robust representative of the data set, any extreme values must be dealt with properly. Extreme values are also known as *outliers*. An *outlier* is defined as "*an observation that is unusually large or small relative to other values in a data set*" (Mendenhall and Sincich, 1988).

In this research, the data set originated from 23 respondents, so can be classified as a small sample ($n<30$). The disadvantage of removing outliers from a small data set is that the data set becomes even smaller. In addition, not all variables had 23 observations. In some categories, the top variables had only 6 or less observations. To keep the robustness of the data set without losing too many observations, it was decided to remove high suspects or definite outliers only from variables with 10 or more observations ($n \geq 10$). Outliers in variables with less than 10 observations were not removed. These outliers were detected using the box plot method. The steps and

examples of calculations for detecting outliers using this method can be found in appendix A8.

As mentioned previously, not all variables had enough observations. For example, there was only 1 respondent who mentioned *cladding* as one type of materials which was typically delivered with the wrong specifications. Hence, this material was not included as one of the materials to be used in the simulation in this category. To avoid underrepresentation, it was then decided that only variables with more than 5 observations (n>5) would be used for the simulation. The final selections of these variables in each flow is shown in table 4-7 below (a bigger version of this table can be found in appendix A9). These supply chain delays were then incorporated into the simulation models which will be described in the next chapter.

Table 4-7 Results of the main survey for the simulation

Information flow					Material flows																						Plant/ equipment / temporary workflow				Labour flow				Workflow (Subcontracted work)				
Activies affected by information delays	prob	delay on start date			Materials delivered later than scheduled delivery dates	Time buffer (days)	prob	delay on start date			Material delivered with wrong specifications	prob	delay on start date			Insuffiecient quantity of materials delivered	prob	delay on duration			Materials damaged on arrival	prob	delay on start date			Difficulties in obtaining materials in the market (Q9)	prob	delay on start date			Plant / temporary work in shortage	prob	delay on duration			Skills in shortage during construction	prob	delay on duration				prob	Delay		
		min	most	max				min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max
Ground works	38%	4	11	22	Steel frame	5	9%	3	5	8	Windows & doors	6%	7	12	35	Briks/blocks	15%	3	6	11	Windows & doors	7%	9	15	27	Fixtures & Fittings	38%	9	15	46	Crane	11%	3	6	15	Bricklayers	26%	5	9	16	Mechanical & Ellectrical	12%	4	7	13
Foundation	16%	3	8	12	Steel reinforcement	6	7%	2	4	7	Bricks/blocks	9%	4	7	15	RM Concrete	6%	1	1	2	Shower cubicles	5%	6	10	15	Bricks (special)	14%	7	12	18	Scaffolding	25%	3	7	11	Joiner	28%	4	7	11	Structural steelwork	8%	3	6	14
Finishes & Decoration	11%	4	7	12	Precast concrete element	5	10%	3	6	10	RM Concrete	15%	1	2	3	Timber	16%	2	5	8	Ceiling	7%	3	6	10	Furniture	32%	4	7	18						Plasterer	27%	4	8	13	Roofwork	16%	6	10	16
Steelwork	39%	5	9	14	Bricks/blocks	7	8%	2	5	11	Roofing materials	6%	4	10	12	Furniture	21%	6	9	15	Bricks/Blocks	6%	10	13	16	Claddings	19%	4	9	15						Plumbers	28%	4	8	13	Brickwork	11%	4	7	12
Fixture & Fittings	55%	5	9	14	Windows & doors	11	16%	4	7	13	Timber	12%	6	7	13	Drainage	23%	4	5	8	Drainage	6%	2	3	4	Tiles	20%	1	12	36						Electrician	28%	4	9	13	Groundwork	8%	3	6	11
Joinery / Ironmongery	43%	4	8	18	Roofing materials	4	10%	3	6	10																Joinery (special)	10%	4	10	14						Steel work erectors	16%	3	5	13	Windows & doors	17%	4	10	18
Windows & Doors	31%	4	7	11																															Scaffolders	16%	2	4	7	Finishings & Decoration	14%	3	6	10
																																			Labourer	11%	1	3	6	Foundation	6%	2	5	7
																																			Concrete gang	10%	2	4	7	Concrete floors	13%	1	6	12
																																							Plastering	26%	6	11	18
																																							Drainage	4%	2	4	8

Chapter 5
The Simulation Models

This chapter presents in detail the process of developing the simulation models for this research, the software used, various scenarios and models, also model verification and validation. It consists of four sections, as follows:

5.1 **Developing the simulation models**: This section basically explains the process of building the simulation models, including the basic assumptions, the nature of the network, the linkage between delays and activities, the arrangement of the delays and how time buffers were modelled.

5.2 **A brief discussion of Pertmaster Risk Expert™ v7.82**: This section gives a short description of the software that is used for the simulation.

5.3 **Running the simulations**: Various scenarios and models are described in this section. It also explains the naming of the models, the optimistic and pessimistic versions, the provision of time buffers, and the trials to determine the right number of iterations.

5.4 **Model verification and validation**: This section describes the definitions, the reasons and techniques of verifying and validating simulation model, including some techniques adopted for this research.

5.1 Developing the simulation models

As mentioned earlier, the research was intended to predict how supply chain management practice may impact on construction project performance. This can be achieved by developing a simulation model that incorporates supply chain delays and running the model with different scenarios. Project risk management software called Pertmaster Risk Expert v7.82 was used to produce the simulation model and the CPM network used was obtained from one of the school projects visited. To build the simulation model, the data obtained from the questionnaire survey was synchronised with activities in the CPM network. In other words, the activities in the CPM network were identified as being linked with possible supply chain delays. The following sections explain this in more detail.

5.1.1 Basic assumptions in the model

In an attempt to reduce the complexity of the simulation model and to fulfil the aims of the simulation, some assumptions were made, as follows:

1. The durations of activities in the CPM network are deterministic, meaning that each activity has only a single duration. The implication of this is that for each activity, it is assumed that a late start will cause a late finish. It is, of course, recognised that the durations of activities in a realistic simulation are subject to variation, but fixing activity duration in this way is very important, as it allows the model to show the impact of supply chain delays on the project which otherwise would not be clearly identified.

2. The frequency of occurrence of the delays is as defined by the respondents and the extent of the delays follows a distribution defined by the three values of minimum, most likely and maximum, also as reported in the questionnaire results.

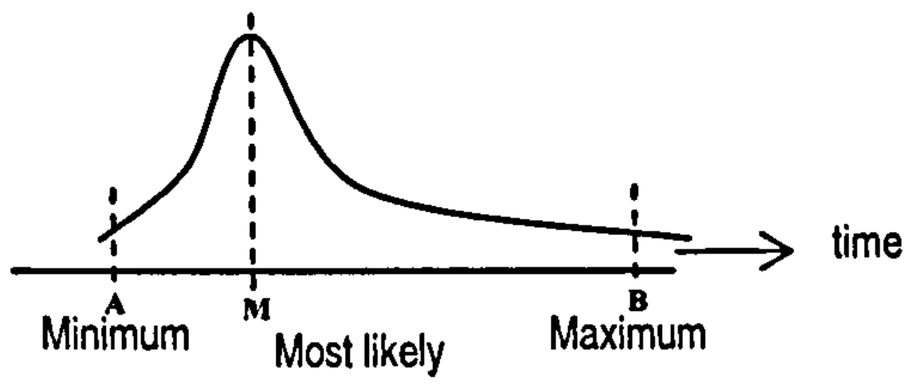


Figure 5-1 A distribution with minimum, most likely and maximum values for the extent of delays

3. Resequencing of activities is not allowed. In practice, when delays occur causing an activity to be unable to start on time or to stop for a period, the site manager might decide to start other activities instead. To be able to clearly show the impact of supply chain delays on the project, however, the current version of the model has no opportunity for such rescheduling. The implication of applying this assumption is that the results of the simulation could be slightly over stated when compared to the real project, as it neglects the opportunity of avoiding delays by managing the sequence of activities in the network.

4. The main contractor is responsible for delays related to material flows and equipment/plant/temporary work and labour flows. For this reason, they may also be called the main contractor delays. Information delay is assumed to be the responsibility of the client.

5. For all subcontracted work, it is assumed that there is only one delay, called the subcontractor delay. This delay, assumed to be the responsibility of the subcontractor, basically encompasses the main contractor delays, i.e. delays related to material flows and equipment/plant/temporary work and labour flows. For subcontracted work, the information delay remains as the responsibility of the client.

6. The materials for an activity are needed on the first day the work commences. For example, it is assumed that the bricks are needed from the very first day of the brickwork activity. Hence, any delay with the bricks' delivery obviously will delay the start date of the brickwork.

5.1.2 Defining the CPM network

As previously mentioned, the CPM network used for the simulation model was obtained from one of the two school projects visited. A medium-sized school was considered to be fairly representative of many medium-sized building projects and one to which most contractors would be able to easily relate. The network was originally in a bar chart form, without links connecting the activities. Links were then added to the network, so that the logic of the activities could be identified, as shown in figure 5-2 below (a bigger version of this figure can be found in appendix A10). From this network, the critical path, the free floats and total floats of activities can be seen. The critical path is the longest path in the network, and if delays occur on any activity along this path, the project completion date will be delayed as a result. The free float shows the amount of time a task can be delayed without delaying its successor tasks, while the total float shows the amount of time that a task can be delayed without delaying the completion of the project.

There are 33 activities in the CPM network which has a project duration of 300 days. The CPM network has 9 paths (see figure 5-2 and table 5-1). Two paths (paths 3 and 7) are critical and there are 19 and 20 activities on these critical paths. The other paths have total floats of 5 (paths 2 and 6), 17 (paths 4 and 8), 46 (paths 1 and 5) and 185 days (path 9). Clearly, these paths can become critical at any time during the simulation, if the total delays to activities which share this total float exceeds the total float. How these non-critical paths may change and become critical will be discussed in section 6.1.1.

Table 5-1 Various paths on the CPM network

Paths	Activities	Total Float (TF)	Activities which share the total float	Note
(a)	**(b)**	**(c)**	**(d)**	**(d)**
1	1*-2-3-4-5-6-7-8-10-11-12-13-18-19-21-22-23-24-25-26*	46 days	12, 13	
2	1*-2-3-4-5-6-7-8-10-11-14-15-16-17-18-19-21-22-23-24-25-26*	5 days	16, 17	
3	**1*-2-3-4-5-6-7-8-10-11-14-15-20-18-19-21-22-23-24-25-26***	**0 day**	-	**Critical**
4	1*-2-3-4-5-6-7-8-10-11-14-15-27-28-29-30-31-22-23-24-25-26*	17 days	27,28,29,30,31	
5	1*-2-3-4-5-6-7-8-9-10-11-12-13-18-19-21-22-23-24-25-26*	46 days	12, 13	
6	1*-2-3-4-5-6-7-8-9-10-11-14-15-16-17-18-19-21-22-23-24-25-26*	5 days	16, 17	
7	**1*-2-3-4-5-6-7-8-9-10-11-14-15-20-18-19-21-22-23-24-25-26***	**0 day**	-	**Critical**
8	1*-2-3-4-5-6-7-8-9-10-11-14-15-27-28-29-30-31-22-23-24-25-26*	17 days	27,28,29,30,31	
9	1*-2-3-32-33-34-35-25-26*	185 days	32,33,34,35	

Note: Activities 1* and 26* are milestones (Start and Finish)

Figure 5-2 The original CPM network with links added

5.1.3 Connecting supply chain delays to activities in the model

To build the simulation models, supply chain delays obtained from the main survey were inserted into the CPM network by matching them with relevant activities in the network. For example, bricks/blocks were identified in the survey as one of the materials which could be a source of delay, as they were likely to be delivered late, delivered with wrong specifications, delivered with insufficient quantity, damaged on arrival or difficult to obtain in the market. Bricklayers were also identified in the survey as one potential delay, as this skill was likely to be in short supply. Clearly, activities in the project which use these materials and skill could be affected as a consequence. In this case, *Substructure brick/blockwork* and *Superstructure brick/blockwork* are the two activities which use these materials and skill, hence they were connected with these delays.

To assist the process of connecting a delay to the relevant activities, a matrix of the supply chain delays and activities was developed, as shown in table 5-2 (a bigger version of this table can be found in appendix A11). This process was started by finding a delay in the top rows, then searching down along the left column to find activities which could be affected by this delay. In the example mentioned above, bricks/blocks are one of materials which can be found under each category of delays in material flow. The next step was to find which activities use these materials in the left column. As mentioned above, activities number 6 and 8, i.e. *Substructure brick/blockwork* and *Superstructure brick/blockwork* are the two activities which use these materials, hence they would be associated with these delays. For other delays, connecting them to relevant activities would be done using the same method. For example, in labour flow, bricklayers, one of the skills in shortage, would be connected to the two activities above, as they would need this skill to carry out the work. This matching process was then repeated until all delays in the top rows were connected to relevant activities in the left column. Having completed this process, it can be seen in table 5-2 that most activities are associated with more than 5 delays and there are also some activities which have almost all the delays from each flow. Having associated the delays with relevant activities, the next step was to arrange the delays in a logical way to represent how they would impact an activity in reality. This will be discussed in the next section.

Table 5-2 Matrix of activities and supply chain delays

Project activities and SC delays

No	Activities	Information flow					Material flows																						Plant/ equipment / temporary workflow				Labour flow				Workflow (Subcontracted work)				
		Activies affected by information delays	prob	delay on start date			Materials delivered later than scheduled delivery dates	Time buffer (days)	prob	delay on start date			Material delivered with wrong specifications	prob	delay on start date			Insufficient quantity of materials delivered	prob	delay on duration			Materials damaged on arrival	prob	delay on start date			Difficulties in obtaining materials in the market (OS)	prob	delay on start date			Plant / temporary work in shortage	prob	delay on duration			Skills in shortage during construction	prob	delay on duration				prob	Delay		
				min	most	max				min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max				min	most	max
		Ground works	38%	4	11	22	Steel frame	5	9%	3	5	8	Windows & doors	6%	7	12	35	Briks/blocks	15%	3	6	11	Windows & doors	7%	9	15	27	Fatures & Fittings	38%	9	15	46	Crane	11%	3	6	15	Bricklayers	26%	5	9	16	Mechanical & Electrical	12%	4	7	13
		Foundation	16%	3	8	12	Steel reinforcement	6	7%	2	4	7	Bricks/blocks	9%	4	7	15	RM Concrete	6%	1	1	2	Shower cubicles	5%	6	10	15	Bricks (special)	14%	7	12	18	Scaffolding	25%	3	7	11	Joiner	28%	4	7	11	Structural steelwork	8%	3	6	14
		Finishes & Decoration	11%	4	7	12	Precast concrete element	5	10%	3	6	10	RM Concrete	15%	1	2	3	Timber	16%	2	5	8	Ceiling	7%	3	6	10	Furniture	32%	4	7	18						Plasterer	27%	4	8	13	Roofwork	16%	6	10	16
		Steelwork	39%	5	9	14	Bricks/blocks	7	8%	2	5	11	Roofing materials	6%	4	10	12	Furniture	21%	6	9	15	Bricks/Blocks	6%	10	13	16	Claddings	19%	4	9	15						Plumbers	28%	4	8	13	Brickwork	11%	4	7	12
		Fixture & Fittings	55%	5	9	14	Windows & doors	11	16%	4	7	13	Timber	12%	6	7	13	Drainage	23%	4	5	8	Drainage	6%	2	3	4	Tiles	20%	1	12	36						Electrician	28%	4	9	13	Groundwork	8%	3	6	11
		Joinery / Ironmongery	43%	4	8	18	Roofing materials	4	10%	3	6	10																Joinery (special)	10%	4	10	14						Steel work erectors	16%	3	5	13	Windows & doors	17%	4	10	18
		Windows & Doors	31%	4	7	11																																Scaffolders	16%	2	4	7	Finishings & Decoration	14%	3	6	10
																																						Labourer	11%	1	3	6	Foundation	6%	2	5	7
																																						Concrete gang	10%	2	4	7	Concrete floors	13%	1	6	12
																																										Plastering	25%	6	11	18
																																										Drainage	4%	2	4	8
1	START																																													
2	SITE ESTABLISHMENT/FENCING						Precast concrete element	5	10%	3	6	10																											Labourer	11%	1	3	6					
3	FORM ACCESS ROAD & REDUCE LEVEL	Ground works	38%	4	11	22																																				Groundwork	8%	3	6	11
4	CONSTRUCT FOUNDATIONS	Foundation	16%	3	8	12							RM Concrete	15%	1	2	3	RM Concrete	6%	1	1	2																Concrete gang	10%	2	4	7	Foundation	6%	2	5	7
5	ERECT STRUCTURAL STEEL FRAME	Steelwork	39%	5	9	14	Steel frame	5	9%	3	5	8																							Crane	0.11	3	6	15	Steel work erectors	16%	3	5	13	Structural steelwork	8%	3	6	14
6	SUBSTRUCTURE BRICK/BLOCKWORK						Bricks/blocks	7	8%	2	5	11	Bricks/blocks	9%	4	7	15	Briks/blocks	15%	3	6	11	Bricks/Blocks	6%	10	13	16	Bricks	14%	7	12	18						Bricklayers	27%	5	10	17	Brickwork	11%	4	7	12
7	CONCRETE FLOOR SLAB						Steel reinforcement	6	7%	2	4	7	RM Concrete	15%	1	2	3	RM Concrete	6%	1	1	2																Concrete gang	10%	2	4	7	Concrete floors	13%	1	6	12
8	SUPERSTRUCTURE BRICK/BLOCK						Bricks/blocks	7	8%	2	5	11	Bricks/blocks	9%	4	7	15	Briks/blocks	20%	3	6	11	Bricks/Blocks	6%	10	13	16	Bricks (special)	14%	7	12	18	Scaffolding	0.25	3	7	11	Bricklayers	26%	5	9	16	Brickwork	11%	4	7	12
9	INSULATION																																						Bricklayers	0.26	5	9	16	Brickwork	11%	4	7	12
10	ROOF JOIST/FRAMEWORK						Roofing materials	4	10%	3	6	10	Roofing materials	6%	4	10	12																		Crane	0.11	3	6	15						Roofwork	16%	6	10	16
11	ROOF COVERINGS						Roofing materials	4	10%	3	6	10	Roofing materials	6%	4	10	12																		Scaffolding	0.25	3	7	11	Scaffolders	16%	2	4	7	Roofwork	16%	6	10	16
12	FASCIAS & SOFFITS												Timber	12%	6	7	13	Timber	16%	2	5	8												Scaffolding	0.25	3	7	11	Scaffolders	16%	2	4	7	Roofwork	16%	6	10	16
13	WINDOWS & DOORS	Windows & Doors	31%	4	7	11	Windows & doors	11	16%	4	7	13	Windows & doors	6%	7	12	35						Windows & doors	7%	9	15	27																	Windows & doors	17%	4	10	18
14	FLOOR SCREED																																										Concrete floors	13%	1	6	12
15	SUSPENDED CEILINGS GRID - TILES	Finishes & Decoration	11%	4	7	12																	Ceiling	7%	3	6	10																	Roofwork	16%	6	10	16
16	FLOOR TILING	Finishes & Decoration	11%	4	7	12																						Tiles	20%	1	12	36											Finishings & Decoration	14%	3	6.4	10
17	PARTITIONS	Finishes & Decoration	11%	4	7	12																																Joiner	28%	4	7	11	Finishings & Decoration	14%	3	6.4	10
18	PLASTERWORK																																					Plasterer	27%	4	8	13	Plastering	26%	6	11	18
19	JOINERY WORKS	Joinery / Ironmongery	43%	4	8	18																						Joinery (special)	10%	4	10	14						Joiner	28%	4	7	11	Finishings & Decoration	14%	3	6.4	10
20	M & E INSTALLATIONS																																					Electrician	28%	4	9	13	Mechanical & Electrical	12%	3.56	7.39	12.71
21	2nd FIX ELECTRICAL																																					Electrician	28%	4	9	13	Mechanical & Electrical	12%	3.56	7.39	12.71
22	DECORATION	Finishes & Decoration	11%	4	7	12																																				Finishings & Decoration	14%	3	6.4	10
23	FURNISHING	Finishes & Decoration	11%	4	7	12												Furniture	21%	6	9	15						Furniture	32%	4	7	18											Finishings & Decoration	14%	3	6.4	10
24	FIXTURES & FITTINGS	Fixture & Fittings	55%	5	9	14																						Fatures & Fittings	38%	9	15	46						Joiner	28%	4	7	11	Finishings & Decoration	14%	3	6.4	10
25	TEST & COMMISSION																																													
26	FINISH																																													
27	IPS FRAMEWORK/PANELING/VANITY UNITS																																					Plumbers	28%	4	8	13					
28	PLUMBING/SANITARYWARE																																					Plumbers	28%	4	8	13					
29	SHOWER CUBICLES																						Shower cubicles	5%	6	10	15																						
30	WALL TILING - SHOWER/TOILET AREAS	Finishes & Decoration	11%	4	7	12																						Tiles	20%	1	12	36											Finishings & Decoration	14%	3	6.4	10
31	VINYL FLOORING	Finishes & Decoration	11%	4	7	12																																						Finishings & Decoration	14%	3	6.4	10
32	DRAINAGE WORKS	Ground works	38%	4	11	22												Drainage	23%	4	5	8	Drainage	6%	2	3	4												Labourer	11%	1	3	6	Drainage	4%	2	4	8
33	EDGE KERBING																																					Labourer	11%	1	3	6					
34	STONE UP & BITMAC FOOTPATHS	Ground works	38%	4	11	22																																Labourer	11%	1	3	6	Groundwork	8%	3	6	11
35	LANDSCAPING	Ground works	38%	4	11	22																																Labourer	11%	1	3	6	Groundwork	8%	3	6	11

5.1.4 Arranging the positions of delays in the models

In general, delays can occur prior to the start of an activity and/or during the activity. When the delays occur prior to the start of an activity, the start date of this activity may be delayed as a consequence. Similarly, when the delays occur during the activity, the duration may be extended so that the finish date may be delayed. Figure 5-3 below shows how both types of delays can be modelled.

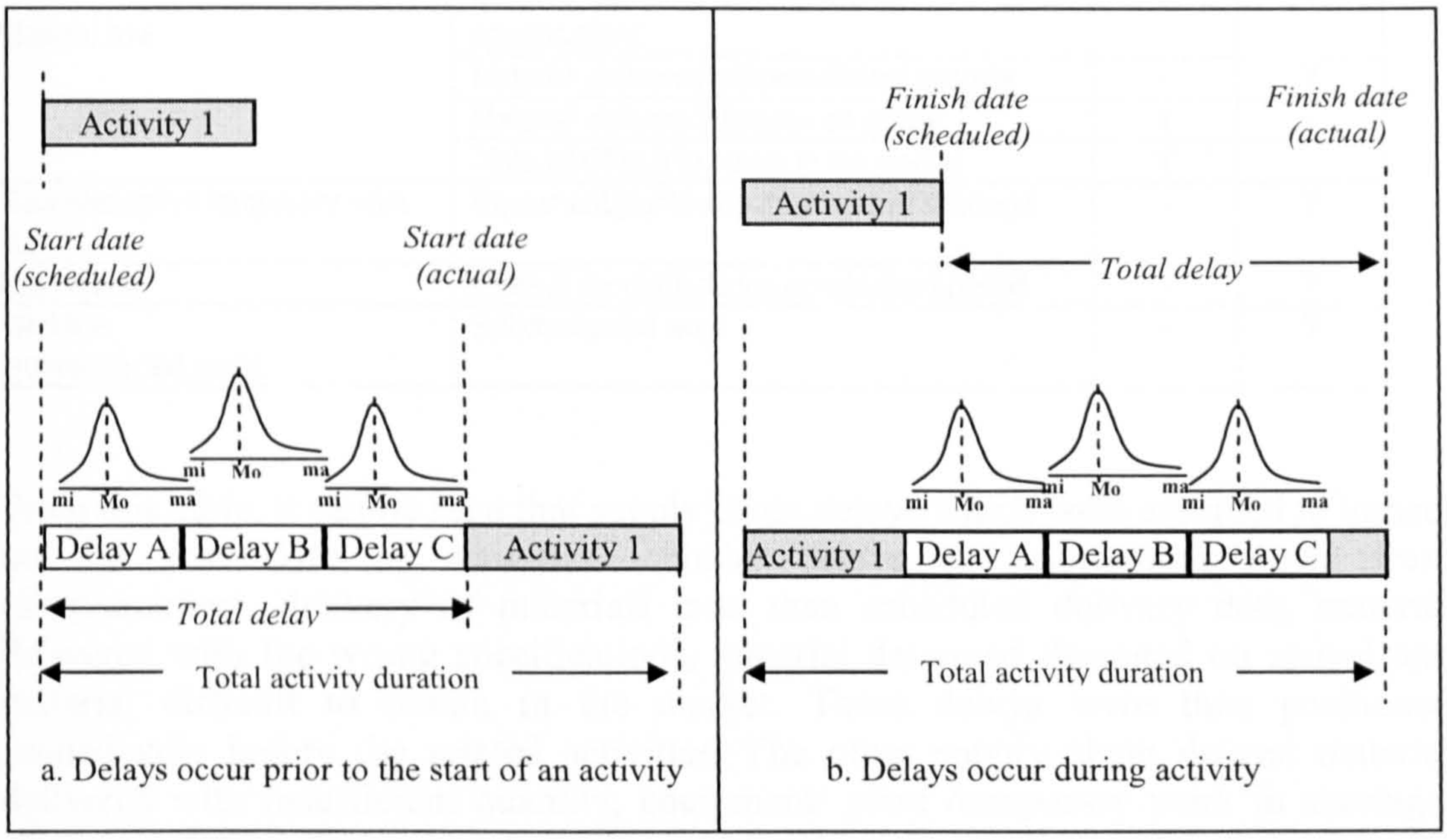


Figure 5-3 Delays may occur prior to the start of an activity or during the activity

The software used in the simulation allows the delays to be placed prior to the start date of an activity, as shown in figure 5-3a, but it does not allow the delays to be inserted into the duration of an activity, as shown in figure 5-3b. To cope with this problem, such delays were positioned following the scheduled finish date of the affected activity.

In practice, it is possible that the same delay may occur prior to the start of an activity and then occur again during the activity. For example, deliveries of materials can be one-off deliveries prior to the start of an activity or multiple deliveries prior to and during an activity, depending on the type of materials or agreement with the suppliers. Similarly, skills shortages can also occur prior to or during an activity, etc. For the simulation, it is necessary to simplify by making assumptions about how the delays may impact on the activities, i.e. delay the activities' start date or extend the activities' duration. These assumptions, for each supply chain delay, are shown in table 5-3 below:

Table 5-3 Assumptions of how supply chain delays impact on start date and duration of an activity

SC delays		Impact on the activity if delays occur	
		Start date	Duration
Information flow	Delays of information flows from client/architect	Y	-
Material flow	Delivery of materials later than scheduled delivery date	Y	-
	Material delivered with the wrong specifications	Y	-
	Material delivered with insufficient quantity	-	Y
	Material delivered damage on arrival	Y	-
	Material difficult to obtain in the market	Y	-
Equipment/plant/temporary work flow	Equipment/plant/temporary work in shortage	-	Y
Labour flow	Skills in shortage during construction period	-	Y
Workflow (subcontracted work)	Subcontracted work	-	Y

From this table, it can be seen that supply chain delays which were assumed to impact on the start date of activities include: delays of information flows from client/architect, delivery of materials later than scheduled delivery date, material delivered with the wrong specifications, material delivered damaged on arrival and material difficult to obtain in the market. These delays were then positioned immediately before the related activities. The other supply chain delays: material delivered with insufficient quantity, equipment/ plant /temporary work in shortage, skills in shortage during construction period and subcontracted works, were assumed to impact on the activities' duration, hence, they were positioned immediately following the activities' scheduled finish dates.

It might be thought that in the model that has been created for this work, it will not matter whether the delays are positioned at the beginning, the middle or the end of an activity, as they will still give the same effect on project duration. However, this is not true. In fact, separating delays at the beginning from delays at the end of an activity means that these 2 sets of delays can never be in parallel, as they will always effectively be in sequence. Therefore, they will affect the project differently. The next section below will discuss how different positions of delays will impact on the project differently.

5.1.5 Combining delays

On a construction project, several delays can occur and impact on an activity consecutively or simultaneously as the following examples illustrate. A package of material was delivered later than the scheduled date (delay A). When it arrived, it was damaged due to careless handling on site (delay B). Since it took several days to get the replacement material, the work using the material could not start on time. Another example to illustrate delays occurring simultaneously is as follows: The bricks were

expected to be delivered on site at a particular time, which did not happen (delay A), while at the same time the bricklayers were not available on site to do the work (delay B). The brickwork could not start on time as a consequence.

To illustrate these two examples in the model, the delays can be positioned either in series for delays occurring consecutively, or in parallel to represent delays occurring simultaneously, as illustrated in figures 5-4a and b. The implication is that for the delays positioned in series, the total delay is simply the sum of each delay, while for the delays positioned in parallel, the total delay is the longest of each separate delay. If the delays are positioned both in series and parallel (figure 5-4c), the longest delay between them will determine the total delay.

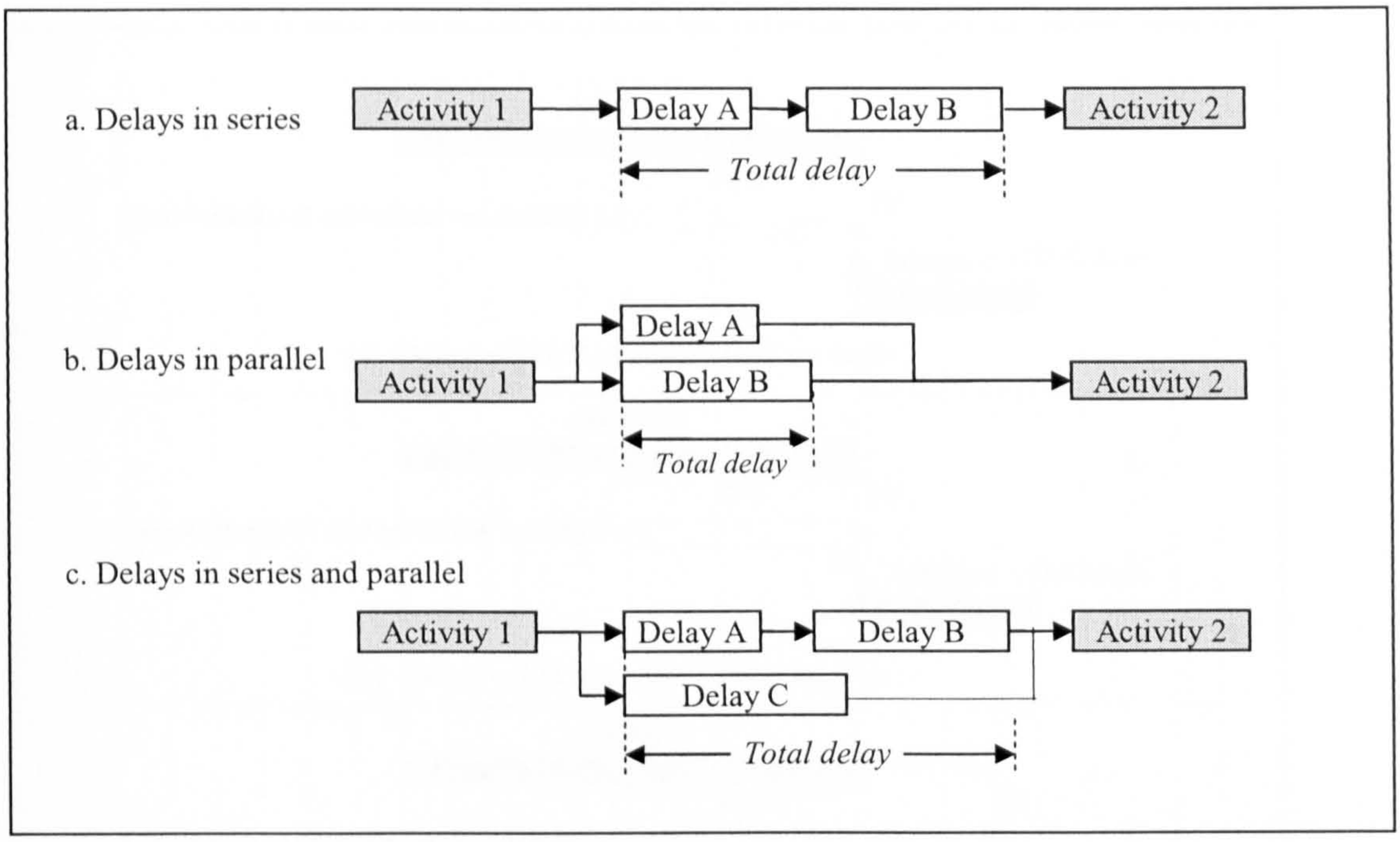


Figure 5-4 Possible positions of delays in the model

Recognising that there are different ways of combining delays as mentioned above, there is an opportunity to make different versions of the models, i.e. optimistic and pessimistic versions. The optimistic version will allow the delays to be arranged in parallel and the pessimistic will allow the delays to be arranged in series. This will be discussed in more detail in section 5.3.1.1.

5.1.6 Modelling time buffers

In practice, to reduce the risk of having work start late due to late delivery of materials or for other reasons, suppliers are sometimes asked to deliver the materials several days in advance of the start date of the activity which needs the materials. In other words, a time buffer is provided to absorb the risk. If this delay (late delivery of materials) does actually occur and its extent is less than or the same as the provided time buffer, the work that needs the materials can still start on time. However, if the

extent of the delay is more than the provided time buffer, the time buffer cannot absorb it all, and hence the work will start late. Figure 5-5 below shows how this is modeled in the simulation. In this example, a 5-day time buffer is provided for activity 2. This means that unless the extent of delay of material delivery is more than 5 days, the activity can still start on time following the completion of activity 1. To model this time buffer, a 5-day negative lag is added to the 'Finish to Start (FS)' link, which links activity 1 and the delay. This negative lag will act as a time buffer and absorb the delay for up to 5 days. To enable activity 2 to start following the completion of activity 1, another 'Finish to Start' link is also added to link activity 1 and activity 2. It can be seen in figure 5-5a that with this 5-day time buffer, when the materials are delivered 2 days late, activity 2 can still start on time. The same situation also happens when the materials are 5 days late (figure 5-5b), however, when the materials are 8 days late, activity 2 is delayed for 3 days (figure 5-5c).

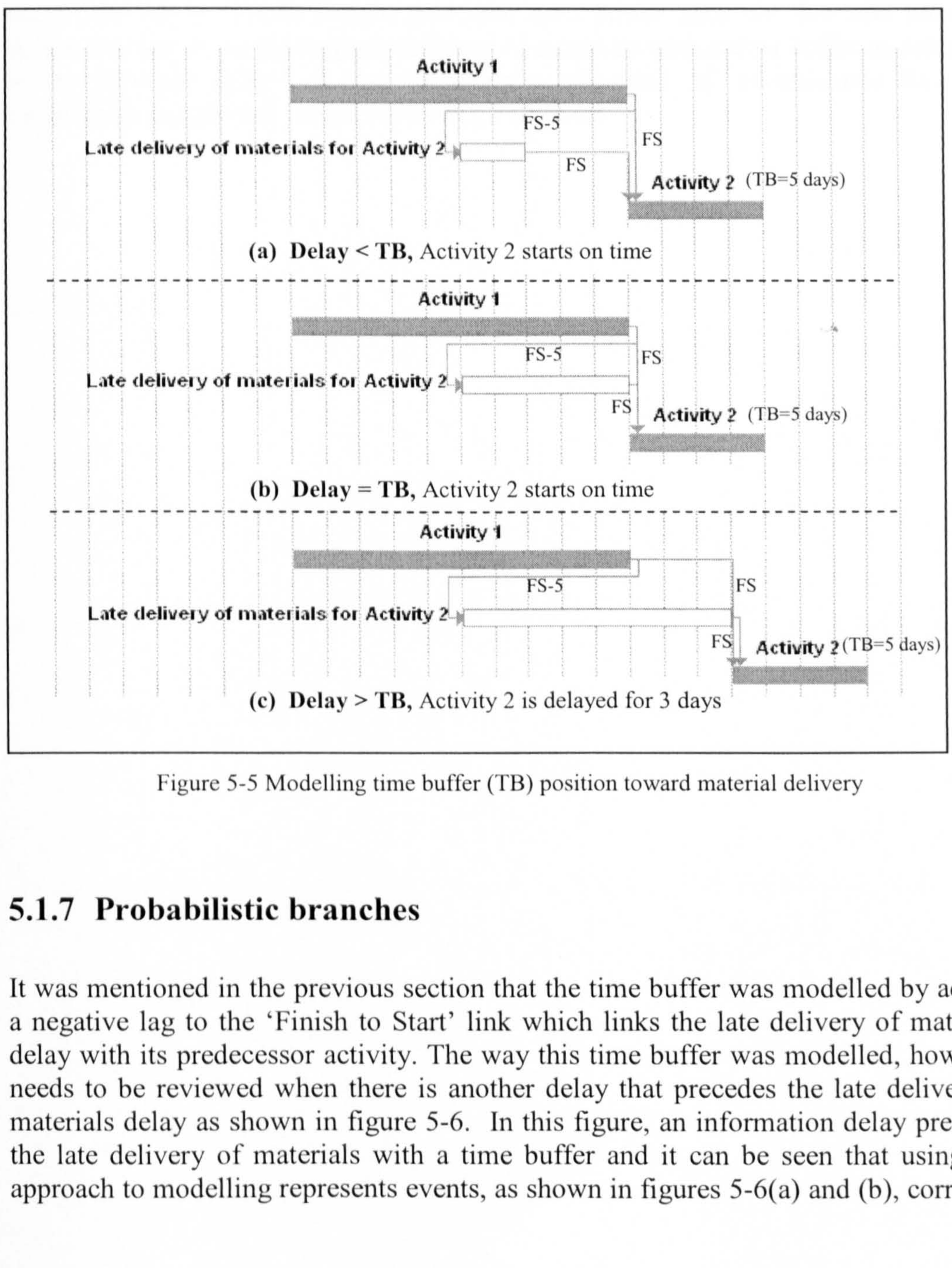


Figure 5-5 Modelling time buffer (TB) position toward material delivery

5.1.7 Probabilistic branches

It was mentioned in the previous section that the time buffer was modelled by adding a negative lag to the 'Finish to Start' link which links the late delivery of materials delay with its predecessor activity. The way this time buffer was modelled, however, needs to be reviewed when there is another delay that precedes the late delivery of materials delay as shown in figure 5-6. In this figure, an information delay precedes the late delivery of materials with a time buffer and it can be seen that using this approach to modelling represents events, as shown in figures 5-6(a) and (b), correctly,

but not the events shown in figure 5-6(c). In figure 5-6(a) there is no delay in information flow, but there is a 3-day delay of late delivery of materials. As there is a 5-day time buffer provided to absorb this 3 day delay, activity 2 can still start on time following the completion of activity 1. In figure 5-6(b), there is a 4-day delay in information flow, but no delay in material delivery, hence the activity is delayed for 4 days. Figure 5-6(c) shows a 4-day delay in information flow and a 3-day delay of late delivery of materials, with a 5-day time buffer. Activity 2 is delayed for 4 days as a result. However, this may not be logical. If the information delay is related to the procurement of the materials (e.g. material specifications, drawings, etc), as a consequence, the materials cannot be delivered until this information is available. This also means that the delay in material delivery can not happen before the information delay. Figure 5-6(d) best describes how these consecutive delays should occur. It shows that when these two delays happen, the late delivery of materials delay can only occur following the delay in information flow. In this case, it can be said that due to the delay in information flow, the time buffer does not function properly. Hence, the way of modelling late delivery of materials with a time buffer as described in the previous section is not sufficient to represent all eventualities for these consecutive delays and, hence, needs to be adjusted.

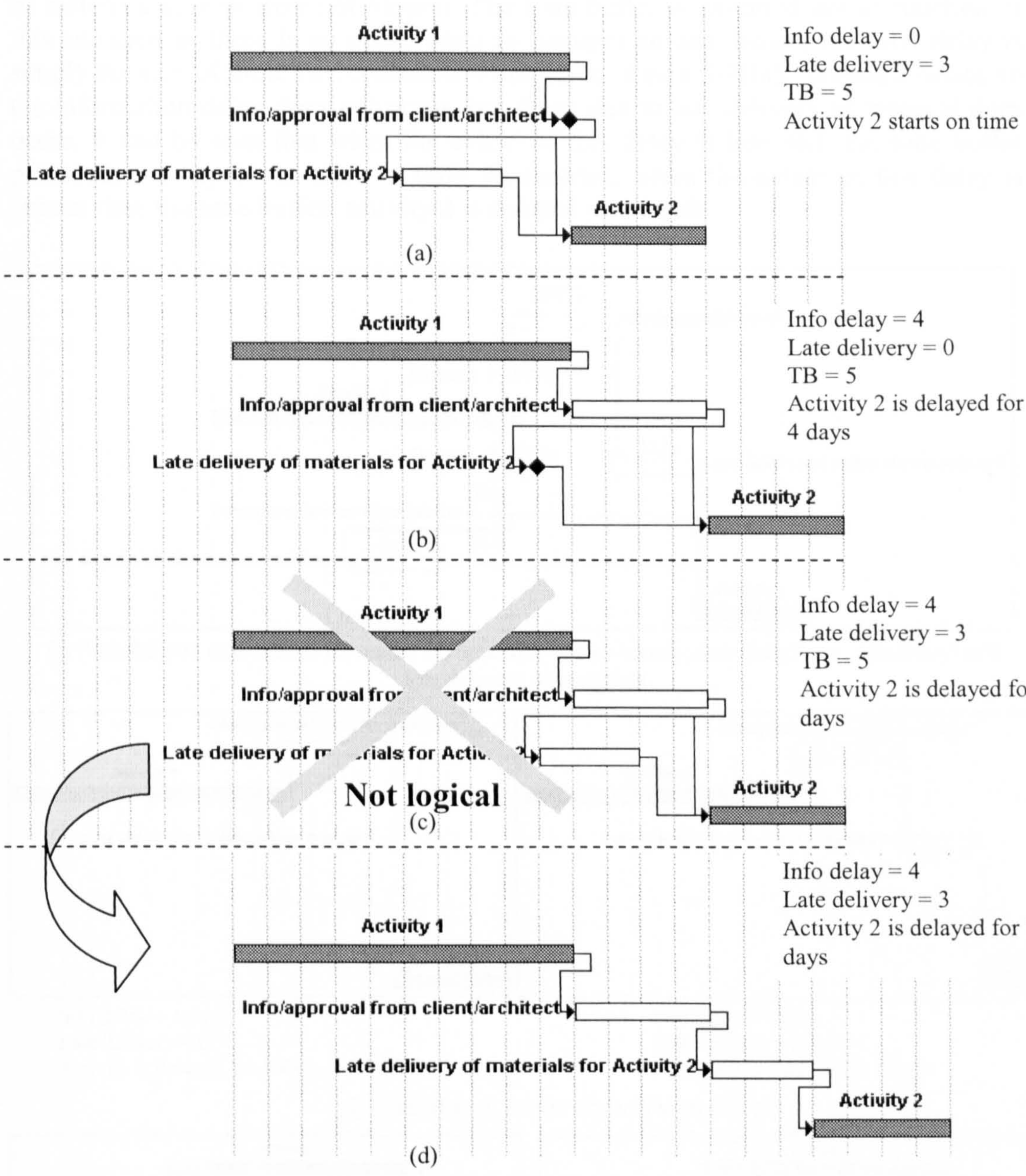
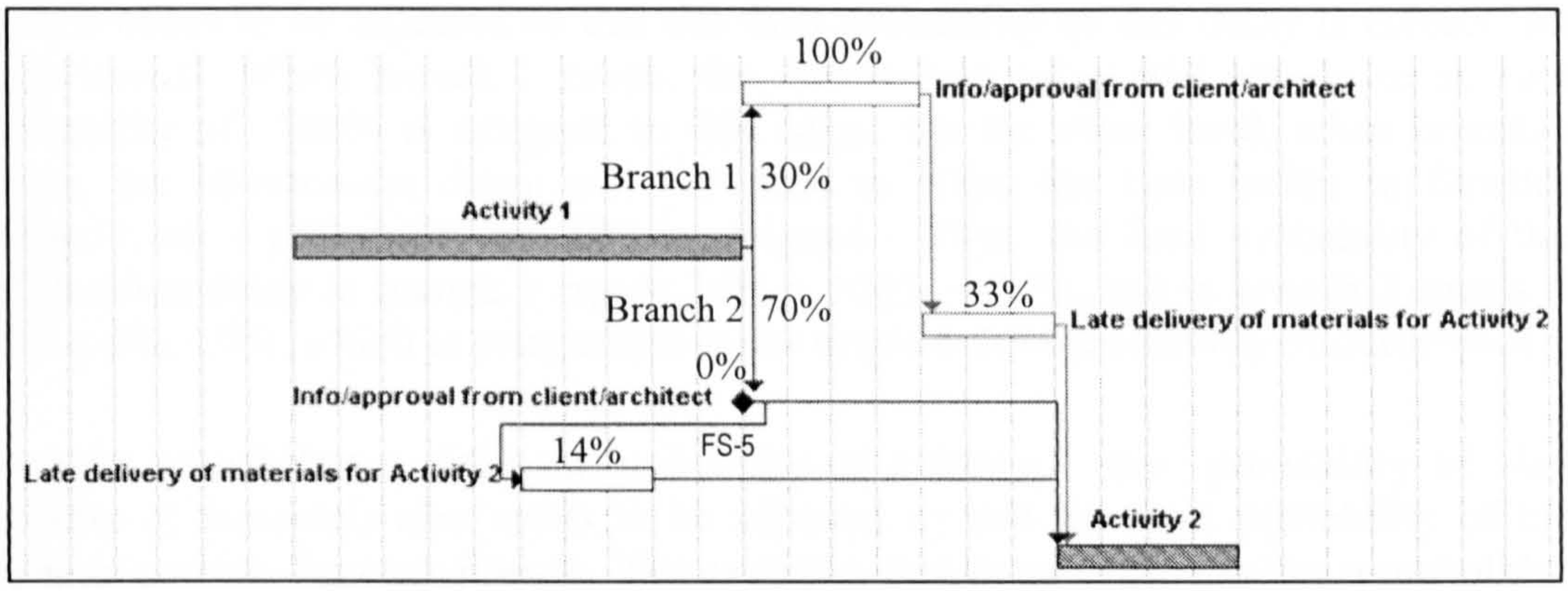


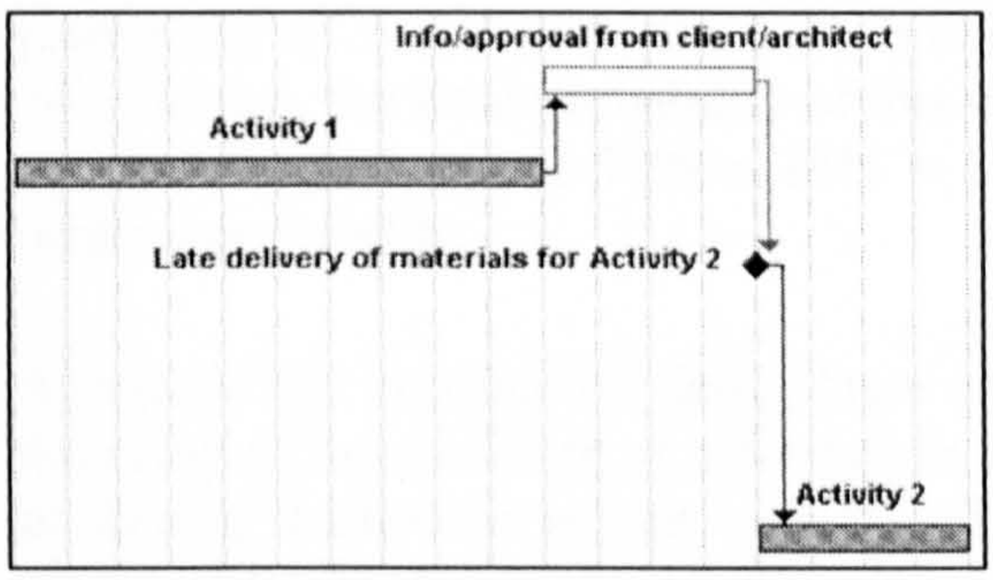
Figure 5-6 Possible events of two two consecutive delays; i.e. info delay and late delivery of materials with a time buffer

This problem of modelling two consecutive delays can be overcome by using probabilistic branches. Probabilistic branches allow modelling of different possible outcomes of activities in the network and they are exclusive, i.e. if one branch exists then the others definitely do not. Figure 5-7(i) below shows how these probabilistic branches can represent eventualities as previously shown by events (a), (b) and (d) in figure 5-6. As they are exclusive, when branch 1 exists, branch 2 does not, and *vice versa*. Branch 1 represents events (b) or (d), i.e. when the information delay occurs, and branch 2 represents event (a), i.e. when no information delay occurs. Figures 5-7(ii) and (iii) visualise examples of possible occurrence of each branch. As shown by figure 5-7(ii), when branch 1 exists, the information delay occurs and late delivery

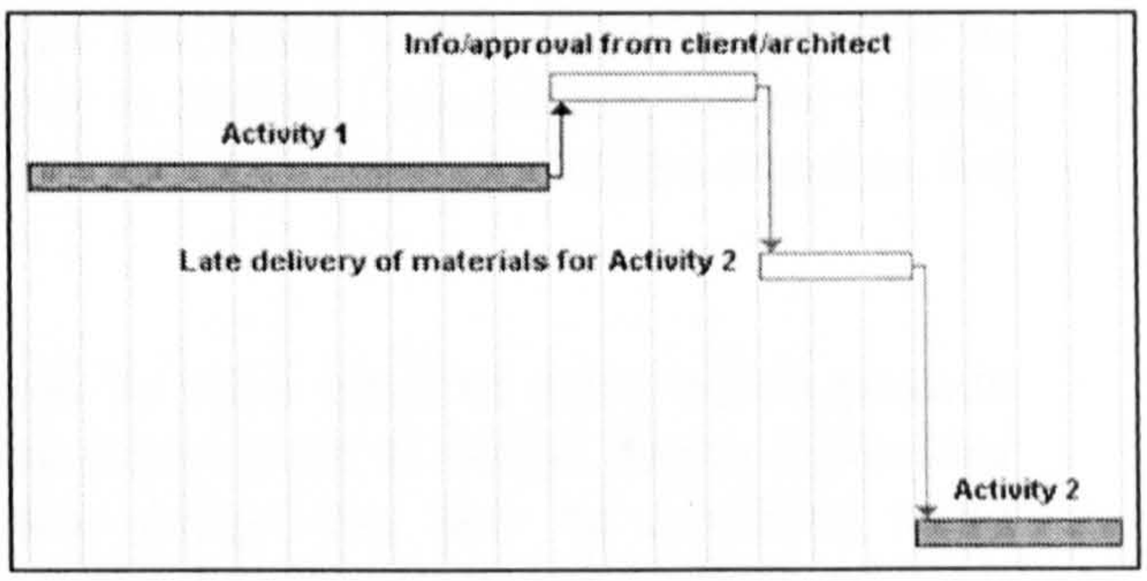
of materials may or may not happen. The time buffer is assumed not to function in this situation as there is no opportunity to incorporate one, hence, the total delay is simply the sum of these two consecutive delays. In figure 5-7(iii), branch 2 exists, so the information delay does not occur, but delay due to late delivery of material does occur. It can be seen that when the extent of this delay is less than the time buffer provided, activity 2 can start on time. In contrast, when the extent of this delay is greater than the time buffer, activity 2 is delayed as a result.



(i) Probabilistic branches to represent eventualities of two consecutive delays; i.e. info delays and late delivery of materials

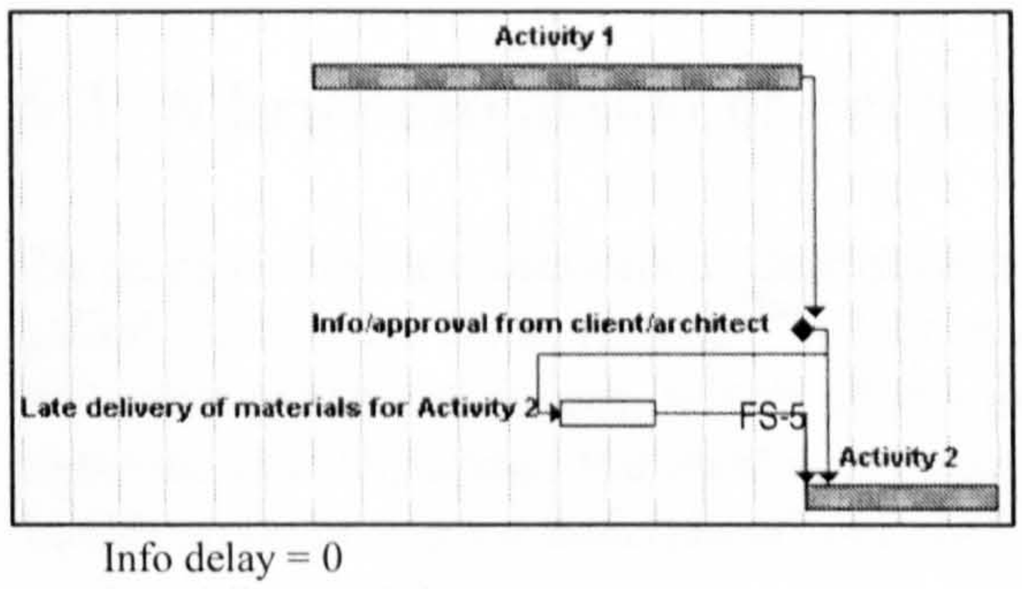


Info delay = 4 days
Late delivery = 0
Activity is delayed for 4 days

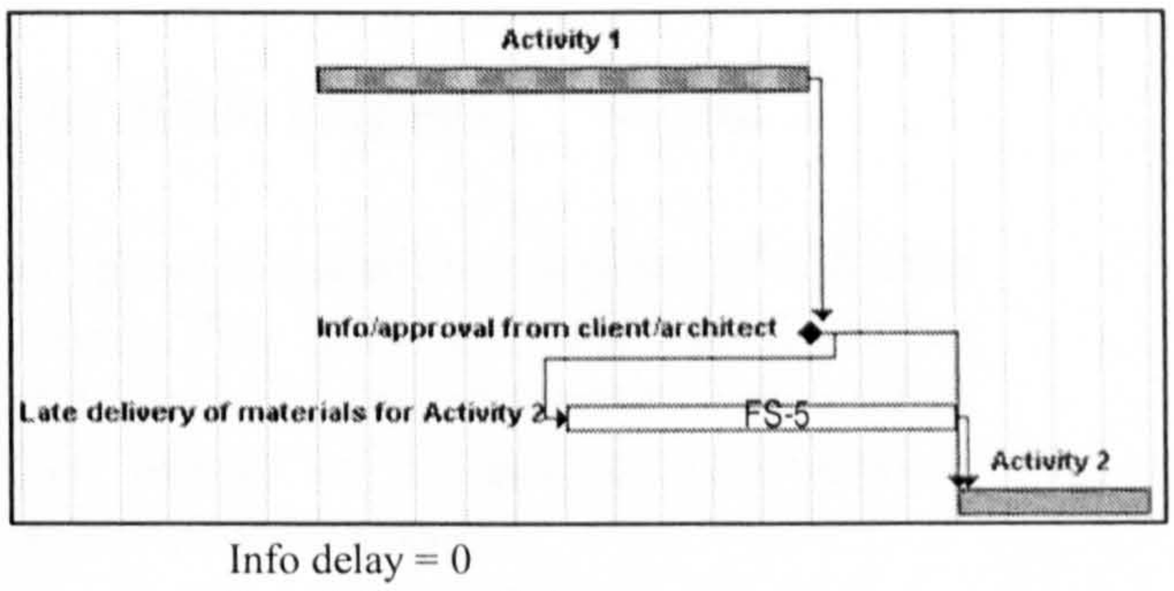


Info delay = 4 days
Late delivery = 3 days
Activity 2 is delayed for 7 days

(ii) Examples of events when Branch 1 exists



Info delay = 0
Late delivery = 2 days
TB = 5 days
Activity 2 starts on time



Info delay = 0
Late delivery = 8 days
TB = 5 days
Activity 2 is delayed for 3 days

(iii) Examples of events when Branch 2 exists

Figure 5-7 Probabilistic branches and possible eventualities

Once these probabilistic branches have been set up, there is the question of how to determine the probability that branch 1 or branch 2 should exist. It should be borne in

mind that in this case, these probabilistic branches relate to the existence of information delay, i.e. branch 1 = information delay exists, branch 2 = information delay does not exist. Therefore, the likelihood can be determined by using the probability of the information delay. For example, the information delay has a probability of occurrence of 30%. This means that the branch 1 will have a 30% chance of existing while branch 2 will have a 70% chance, as shown by figure 5-7(i). Since the probability of the information delay has already been transferred in advance to the probabilistic links, the probability of an information delay occurring on each branch needs to be adjusted so that the final probability of this delay is correct for each branch. When branch 1 exists, the information delay will always exist, so a probability of 100% is assigned to this delay. On the other hand, when branch 2 exists, the information delay will not exist to allow the time buffer to function properly, so a probability of 0% is assigned. Thus, the final probability of this information delay in branch 1 equals 30% x 100% = 30%, and in branch 2 equals to 70% x 0% = 0%, which is comparable to the original 30% probability of occurrence.

As each branch has a different probability of existing, the probability of *late delivery of materials* also needs to be adjusted so that the final probability of this delay is correct for each branch. For example, this delay originally has a probability of occurrence of 10%. As branch 1 has a 30% probability of occurrence, the probability of this delay should be adjusted to 33%. In branch 2, which has a 70% probability of occurrence, the probability of this delay should then be adjusted to 14%. Hence, the final probability of this delay in branch 1 equals 30% x 33% = 10%, and in branch 2 equals 70% x 14% = 10%, which is correct and the same as the original probability.

Alongside the information delay, there could be other types of delay which precede the delay of *late delivery of materials* in the model, such as delays due to *difficulties in finding materials in the market.* These delays can also be modelled using probabilistic branches as shown above, with the necessary adjustment of their probability of occurrence.

5.2 A brief discussion of Pertmaster Risk Expert™ v7.82

To carry out the simulations as described in the previous sections, a piece of software called Pertmaster Risk Expert™ v7.82 was used. This is monte carlo-based project risk management software, which allows probabilistic risks to be inserted into a CPM network and simulates the model to learn their impact on the project. The network itself can be produced beforehand with MS Project or Primavera.

To be able to run a simulation, there are two basic inputs needed for the risks, i.e. risk existence and risk duration. The risk existence is the probability that the risk will occur, stated in percentage terms. The risk duration is represented by a range of durations for the risk if it does occur. Some options for risk distributions are available, such as Triangular, Uniform, Normal, BetaPert, etc. For the simulation reported in this research, BetaPert distribution was used, as this type of distribution is

argued suitable for representing construction activity duration (AbouRizk and Halpin, 1992, Law and Kelton, 2000). This software also allows the modelling of probabilistic branches or probabilistic links which is useful to model activities or risks which have more than one route or scenario. The criticality index (CI) and duration sensitivity (DS) of activities in the network, which are important to understand the nature of the model, can also be determined using this software. The criticality index indicates the percentage of time activities appear on the critical path during simulations, while duration sensitivity measures the correlation between the activity duration including associated delays and the project duration.

From the description above, it is clear that Pertmaster Risk Expert is an adequate tool for carrying out the simulations needed for this research as the supply chain delays can be considered as risks which may impact on the project. Figure 5-8 below is a snapshot of the software showing part of the network and the supply chain delays, together with a window for inputting the risk parameters. It should be noted, however, that although this software can produce fine graphical outputs, it was necessary to reproduce and customise them manually using MS Excel to suit the requirement of this thesis. That is because while this software can only produce a single output in one graph, some sections in this thesis require multiple outputs from different models to be produced in one graph, so that they can be compared with each other more easily, as illustrated by figures 6-9 and 6-13 in the next chapter. Both figures show comparisons of two outputs which are produced in one graph, i.e. optimistic and pessimistic models, and models with and without time buffers. In addition, this reproduction also allows multiple graphs to be shown in one page to support the discussions in the thesis, and to produce efficient appendices.

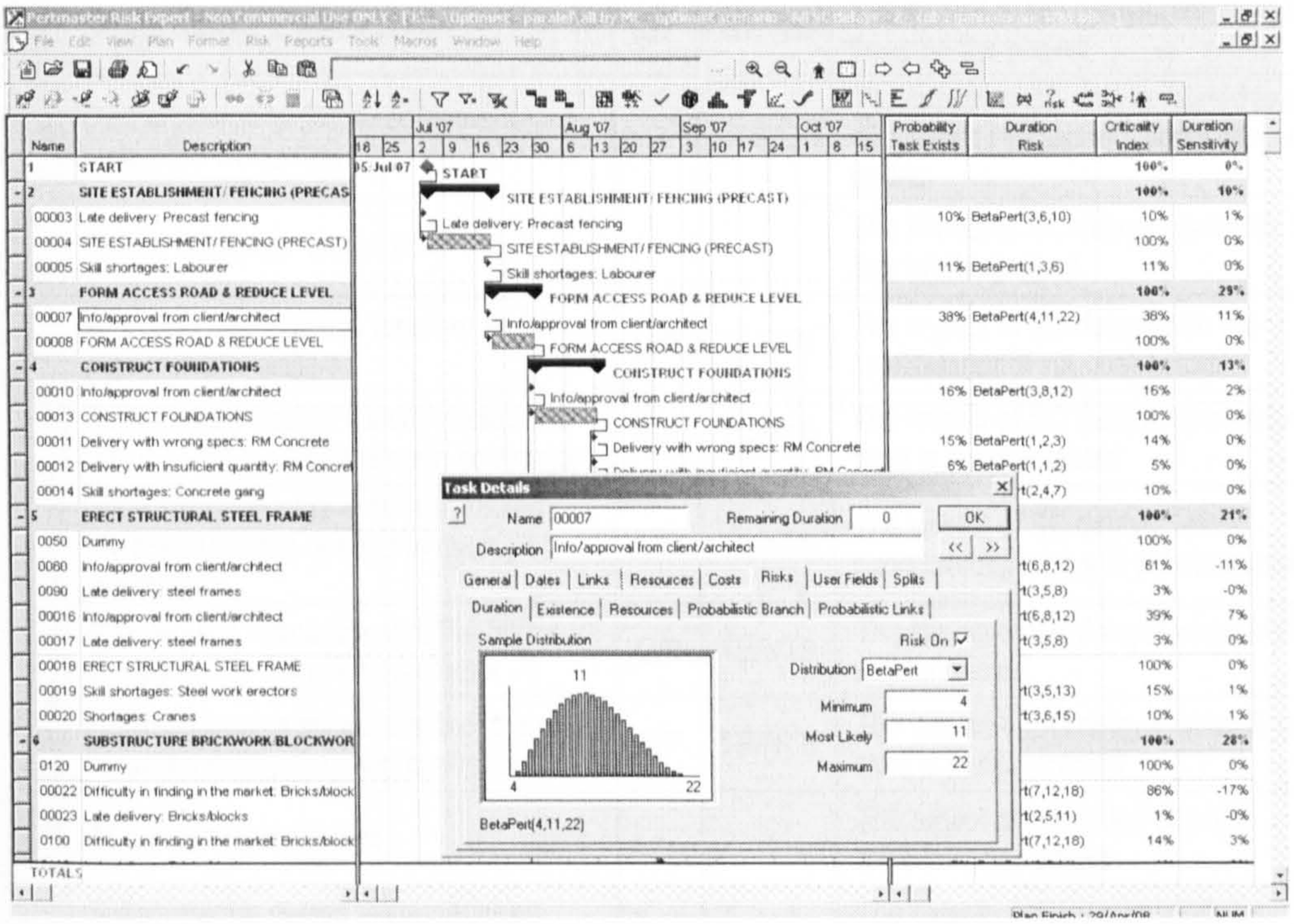


Figure 5-8 A snapshot of Pertmaster Risk Expert

5.3 Running the simulations

5.3.1 Scenarios that can be tested

To understand the impact of supply chain delays on the project, there are various scenarios that can be tested, as shown in table 5-4 below. Basically these scenarios can be categorised into two groups, i.e. when all work is carried out by the main contractor and when subcontractors are used in the project. The supply chain delays are applied all together or one at a time in both groups to learn how the project is affected by them as a whole or partially. To represent the reality that these delays may happen at the same time or one after another, some models have optimistic and pessimistic versions. The optimistic version allows the delays to be arranged in parallel, while the pessimistic version allows them to be positioned in series. For some models, there is also an opportunity to understand the impact of providing time buffers for materials flow. The details of the optimistic/pessimistic versions and the provision of time buffers will be discussed in sections 5.3.1.1 and 5.3.1.2.

Table 5-4 Various scenarios to be tested

	Scenarios	O/P	TB/NTB	What can be learnt
All the work is carried out by the main contractor	All supply chain delays together	O/P	TB/NTB	The impact of SC delays on the project
	Delays related to information flow	-	-	The impact of delays related to information flow on the project
	Delays related to Material flow	O/P	TB/NTB	The impact of SC delays related to material flows on the project
	Delays related to Plant / equipment / temporary works flow	-	-	The impact of SC delays related to plants / equipment / temporary works flows on the project
	Delays related to labour flow	-	-	The impact of SC delays related to labour flow on the project
Subcontractors are used to carry out the work that is normally subcontracted	All supply chain delays together and all subcontractor delays	O/P	TB/NTB	The impact of SC delays with the involvement of subcontractors
	Substructure work is subcontracted, the rest is carried out by the main contractor	O/P	TB/NTB	The impact of SC delays when substructure work is subcontracted
	Superstructure work is subcontracted, the rest is carried out by the main contractor	O/P	TB/NTB	The impact of SC delays when superstructure work is subcontracted
	M&E work is subcontracted, the rest is carried out by the main contractor	O/P	TB/NTB	The impact of SC delays when M&E work is subcontracted
	Finishing work is subcontracted, the rest is carried out by the main contractor	O/P	TB/NTB	The impact of SC delays when finishing work is subcontracted
	All subcontractor delays	-	-	The extent of delay due solely to subcontractor delays
	Subcontractor delays in substructure work	-	-	The extent of delay due solely to subcontractor delays in substructure work
	Subcontractor delays in superstructure work	-	-	The extent of delay due solely to subcontractor delays in superstructure work

	Scenarios	O/P	TB/NTB	What can be learnt
	Subcontractor delays in M&E work	-	-	The extent of delay due solely to subcontractor delays in M&E work
	Subcontractor delays in finishing work	-	-	The extent of delay due solely to subcontractor delays in finishing work

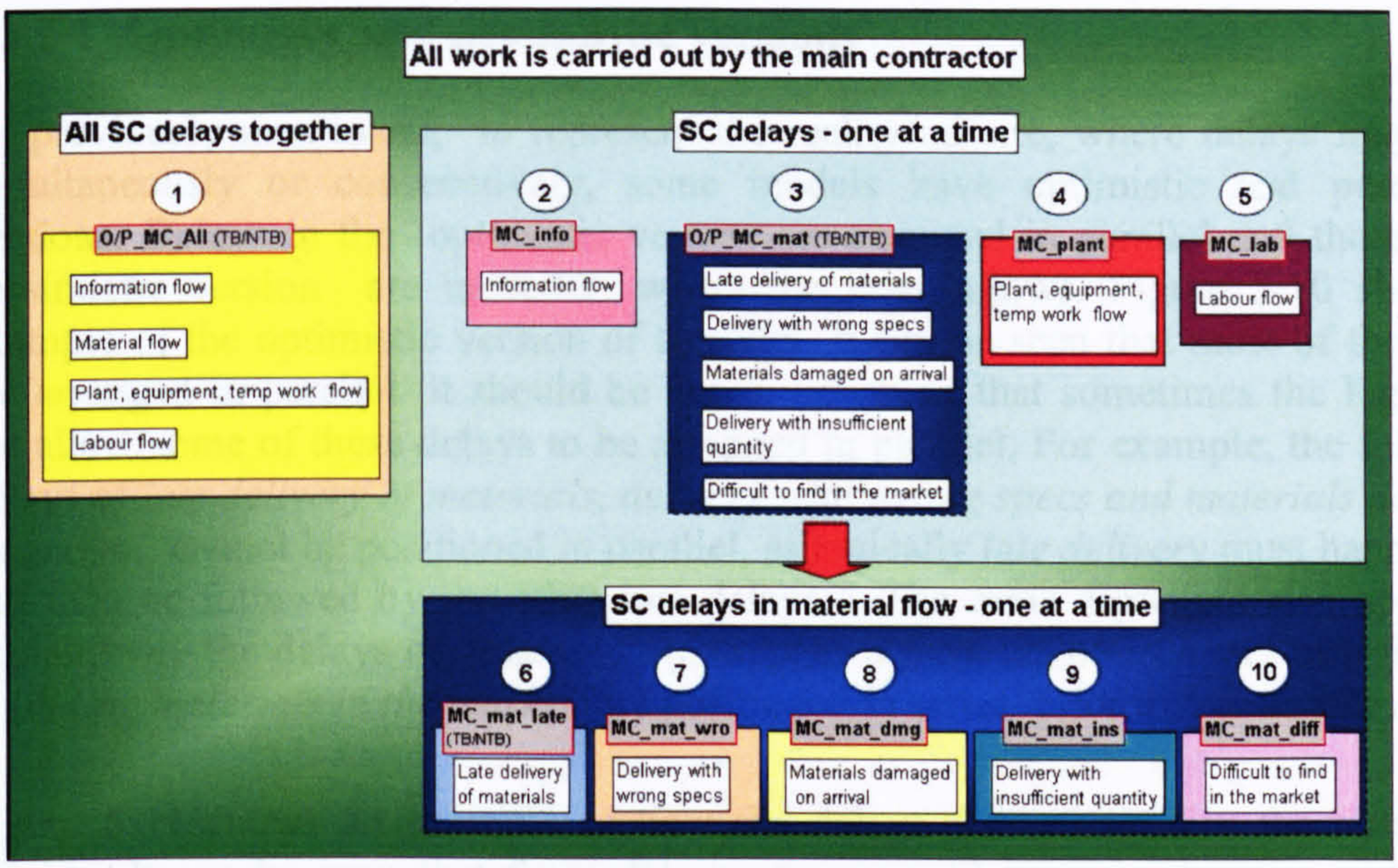
Note:
SC=Supply Chain, O/P=Optimistic/Pessimistic versions, TB/NTB=with Time Buffer/No Time Buffer

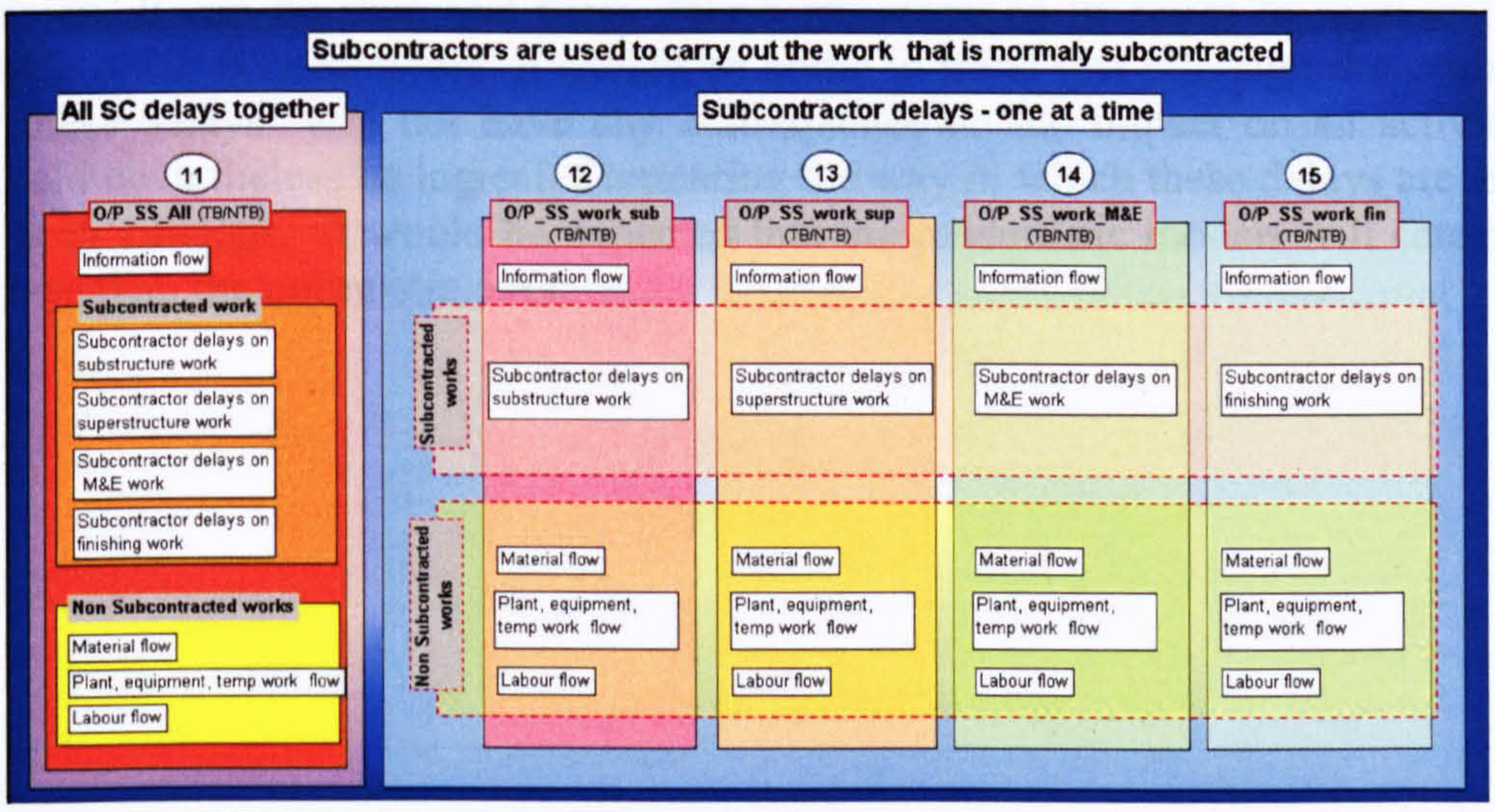
Figure 5-9 shows the scenarios in more detail. It can be seen that there are 20 models to represent the scenarios above with details of delays to be included in each model. For identification, all these models are numbered and named with terms which can be easily associated with the relevant delays or scenarios, as shown in table 5-5 below.

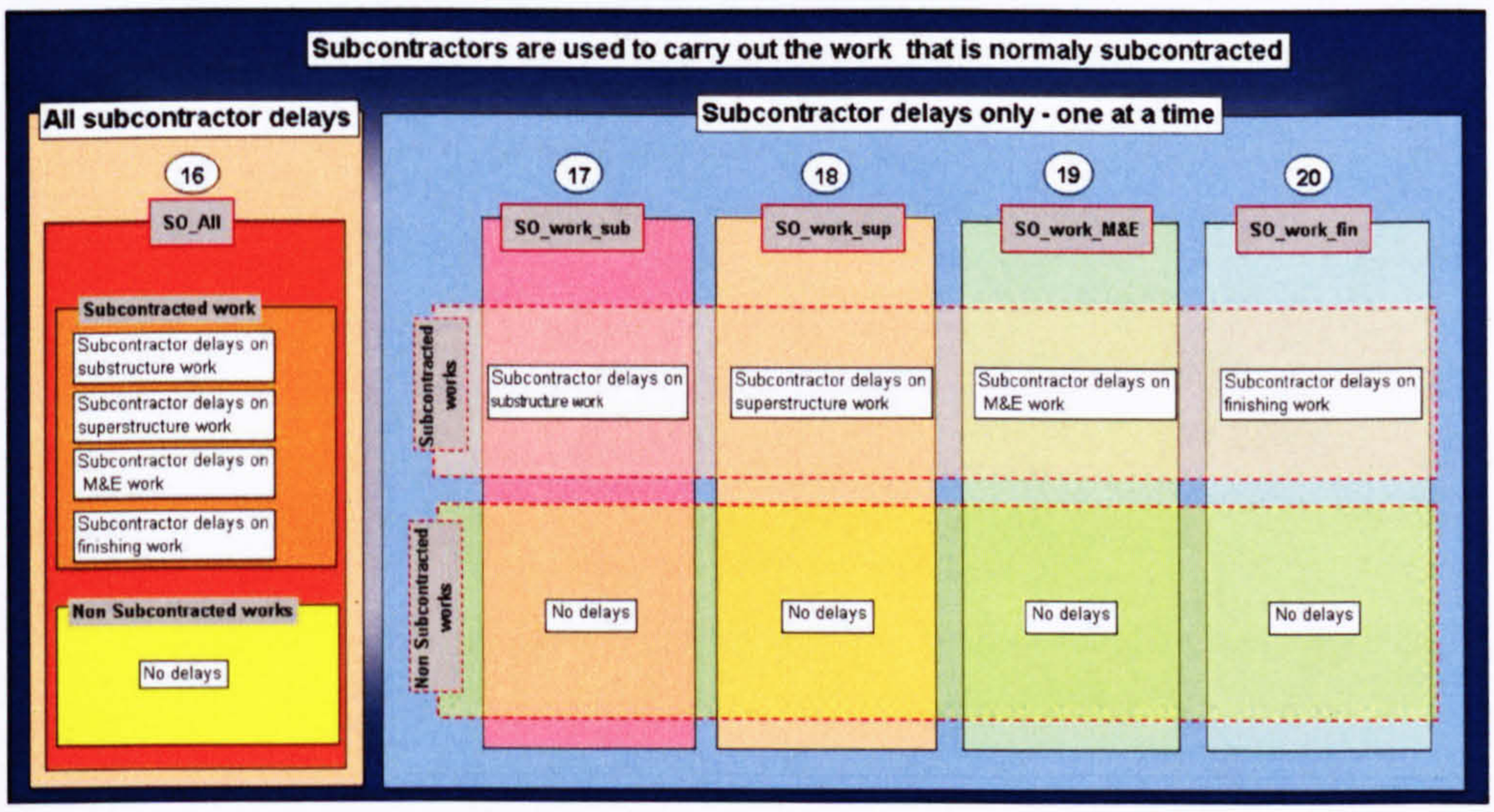
Table 5-5 Terms used for naming the models and associated delays or scenarios

Terms	Relevant delays or scenarios
O/P_	Optimistic/Pessimistic versions
MC_	All work is carried out by the main contractor
SS_	Subcontractors are used to carry out the work that is normally subcontracted
SO_	Only subcontractor delays are applied in the model
(TB/NTB)	(With) Time buffer / No Time Buffer
_all	All delays included
_info	Delays related to information flow
_mat	Delays related to material flow
_plant	Delays related to plant, equipment and temporary work flow
_lab	Delays related to labour flow
_late	Delays related to late delivery of materials
_wro	Delays related to wrong specifications of materials
_dmg	Delays related to material damaged on arrival
_ins	Delays related to insufficient quantity of material
_diff	Delays related to difficulties in finding/sourcing material
_sub	Subcontractor delays in substructure work
_sup	Subcontractor delays in superstructure work
_M&E	Subcontractor delays in M&E work
_fin	Subcontractor delays in finishing work

Once the results of the simulations from the various models have been obtained, they can be considered either individually or compared one result with another to appreciate the variability of project performance due to various supply chain delays. The simulation results should also allow an understanding of which of the delays has the greatest impact on project performance.


All work is carried out by the main contractor
All SC delays together
1
O/P_MC_All (TB/NTB)
Information flow
Material flow
Plant, equipment, temp work flow
Labour flow
SC delays - one at a time
2
MC_info
Information flow
3
O/P_MC_mat (TB/NTB)
Late delivery of materials
Delivery with wrong specs
Materials damaged on arrival
Delivery with insufficient quantity
Difficult to find in the market
4
MC_plant
Plant, equipment, temp work flow
5
MC_lab
Labour flow
SC delays in material flow - one at a time
6
MC_mat_late (TB/NTB)
Late delivery of materials
7
MC_mat_wro
Delivery with wrong specs
8
MC_mat_dmg
Materials damaged on arrival
9
MC_mat_ins
Delivery with insufficient quantity
10
MC_mat_diff
Difficult to find in the market


Subcontractors are used to carry out the work that is normaly subcontracted
All SC delays together
11
O/P_SS_All (TB/NTB)
Information flow
Subcontracted work
Subcontractor delays on substructure work
Subcontractor delays on superstructure work
Subcontractor delays on M&E work
Subcontractor delays on finishing work
Non Subcontracted works
Material flow
Plant, equipment, temp work flow
Labour flow
Subcontractor delays - one at a time
12
O/P_SS_work_sub (TB/NTB)
13
O/P_SS_work_sup (TB/NTB)
14
O/P_SS_work_M&E (TB/NTB)
15
O/P_SS_work_fin (TB/NTB)
Information flow
Subcontracted works
Subcontractor delays on substructure work
Subcontractor delays on superstructure work
Subcontractor delays on M&E work
Subcontractor delays on finishing work
Non Subcontracted works
Material flow
Plant, equipment, temp work flow
Labour flow


Subcontractors are used to carry out the work that is normaly subcontracted
All subcontractor delays
16
SO_All
Subcontracted work
Subcontractor delays on substructure work
Subcontractor delays on superstructure work
Subcontractor delays on M&E work
Subcontractor delays on finishing work
Non Subcontracted works
No delays
Subcontractor delays only - one at a time
17
SO_work_sub
18
SO_work_sup
19
SO_work_M&E
20
SO_work_fin
Subcontracted works
Subcontractor delays on substructure work
Subcontractor delays on superstructure work
Subcontractor delays on M&E work
Subcontractor delays on finishing work
Non Subcontracted works
No delays

5.3.1.1 Optimistic and pessimistic versions

As previously mentioned, to represent the reality on site, where delays may occur simultaneously or consecutively, some models have optimistic and pessimistic versions. Delays in the optimistic version are arranged in parallel and those in the pessimistic version are in series, where the logic allows. Figure 5-10 shows an example of the optimistic version of a model. It can be seen that most of the delays are arranged in parallel. It should be noted, however, that sometimes the logic does not allow some of these delays to be arranged in parallel. For example, the following delays of *late delivery of materials, delivery with wrong specs and materials damaged on arrival* cannot be positioned in parallel, as logically *late delivery* must happen first and then be followed by the other two delays. The same argument also applies to explain why the delays of obtaining *info/approval from client/architect* or *difficulties in finding materials in the market* are positioned in series prior to *late delivery*.

Figure 5-11 shows an example of how the delays are arranged in the pessimistic version. It can be seen that these delays are arranged in series to represent delays which occur consecutively. It should be borne in mind that although the actual order of these delays will not have any consequence on the impact on an activity, they should nevertheless be logical. Comparing the way in which these delays are arranged in both versions, it would be expected that the pessimistic models will cause longer delays than the optimistic ones.

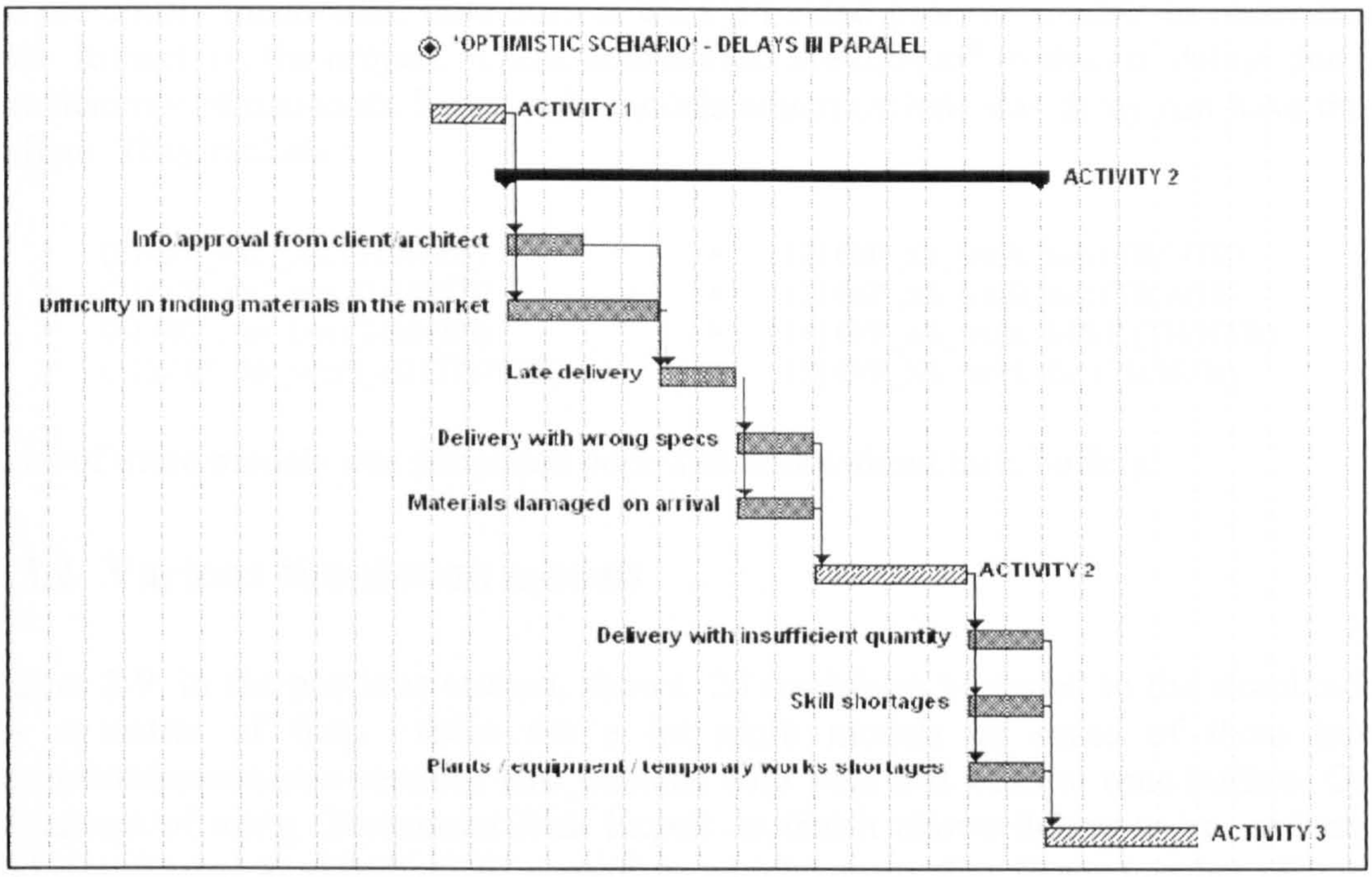


Figure 5-10 The arrangement of the supply chain delays in optimistic models

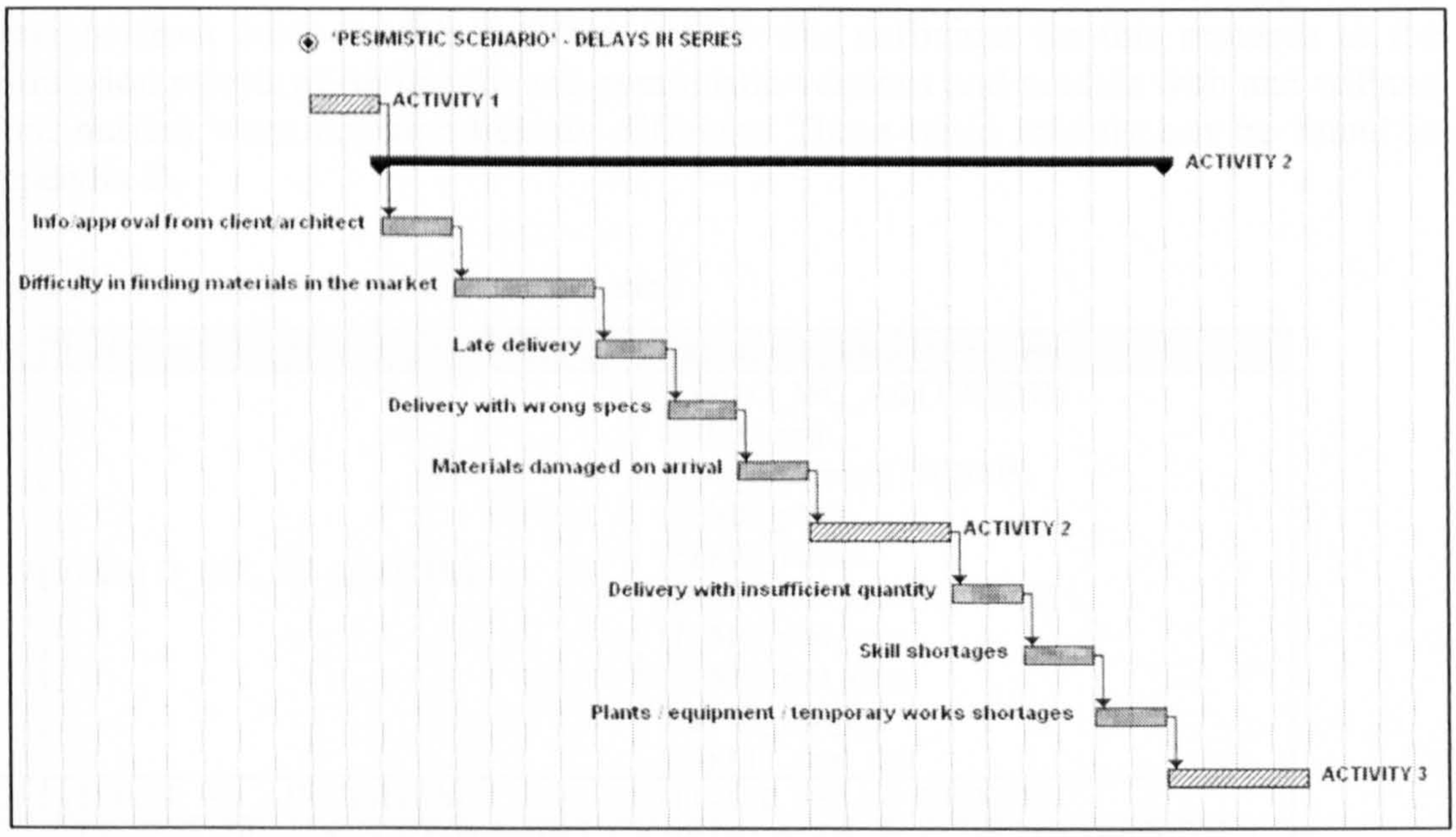


Figure 5-11 The arrangement of the supply chain delays in pessimistic models

5.3.1.2 Provision of time buffers

As previously mentioned, time buffers were provided in some models to understand their impact on the project. These time buffers are intented to absorb delays due to late delivery of materials, hence only models which include this delay can have time buffers. They include :

- (1) O/P_MC_All (TB/NTB)
- (3) O/P_MC_mat (TB/NTB)
- (6) MC_mat_late (TB/NTB)
- (11) O/P_SS_work_all (TB/NTB)
- (12) O/P_SS_work_sub (TB/NTB)
- (13) O/P_SS_work_sup (TB/NTB)
- (14) O/P_SS_work_M&E (TB/NTB)
- (15) O/P_SS_work_fin (TB/NTB)

Each of these models was simulated both with and without time buffers.

5.3.2 Various simulation models

Figure 5-9, in the previous section, shows 20 models to be tested in the simulation. As a matter of fact, there are a lot more models as some of them have optimistic/pessimistic versions and versions both with and without time buffers. One advantage of using Pertmaster Risk Expert is that it allows delays to be activated and deactivated to suit diverse scenarios, which means that fewer number of basic simulation models needed to be prepared for all the scenarios. Table 5-6 shows that a few basic models could be used for other models, i.e. by activating and deactivating the relevant delays. Later, it was found during the trials that developing various versions from basic models numbers 1 to 8 was sufficient for this research as the simulation results of optimistic and pessimistic versions and models with and without time buffers were not significantly different. These basic models can be found in appendix B.

Table 5-6 Basic models for all versions/scenarios

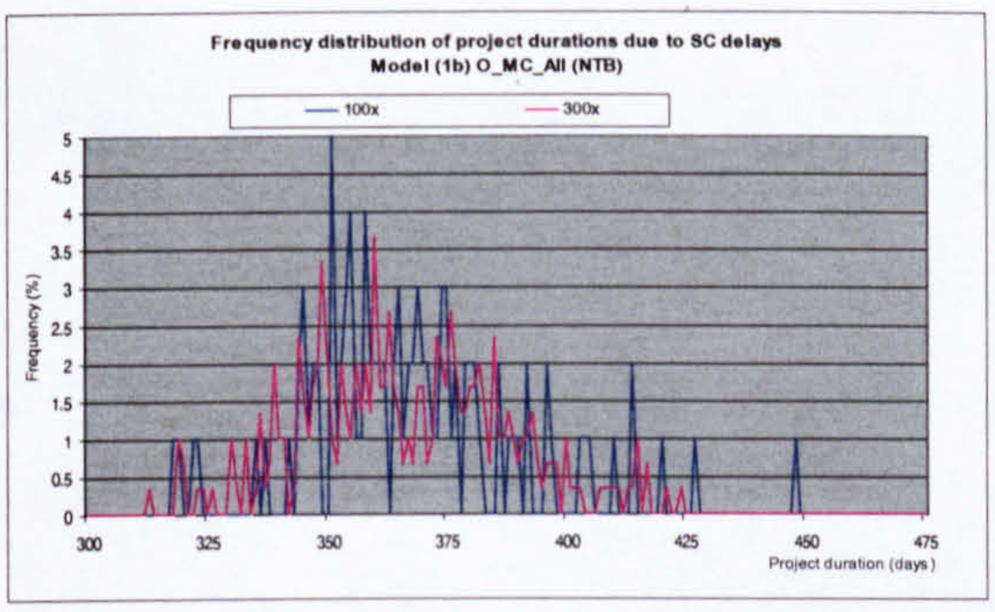
No	Basic models	Can also be used for models
1	(1a/b) O_MC_All (TB/NTB)	(1a/b) O_MC_All (TB/NTB) (2) MC_info (3) O_MC_mat (TB/NTB) (4) MC_plant (5) MC_labour (6) MC_mat_late (TB/NTB) (7) MC_mat_wro (8) MC_mat_dmg (9) MC_mat_ins (10) MC_mat_diff
2	(11) O/P_SS_All (TB/NTB)	(11) O/P_SS_All (TB/NTB)
3	(12a/b) O_SS_work_sub (TB/NTB)	(12a/b) O_SS_work_sub (TB/NTB)
4	(13a/b) O_SS_work_sup (TB/NTB)	(13a/b) O_SS_work_sup (TB/NTB)
5	(14a/b) O_SS_work_M&E (TB/NTB)	(14a/b) O_SS_work_M&E (TB/NTB)
6	(15a/b) O_SS_work_fin (TB/NTB)	(15a/b) O_SS_work_fin (TB/NTB)
7	(16) SO_All	(16) SO_All (17) SO_work_sub (18) SO_work_sup (19) SO_work_M&E (20) SO_work_fin
8	(1b/d) P_MC_All (TB/NTB)	(1b/d) P_MC_All (TB/NTB)
9	(12b/d) P_SS_work_sub (TB/NTB)	(12b/d) P_SS_work_sub (TB/NTB)

No	Basic models	Can also be used for models
10	(13b/d) P_SS_work_sup (TB/NTB)	(13b/d) P_SS_work_sup (TB/NTB)
11	(14b/d) P_SS_work_M&E (TB/NTB)	(14b/d) P_SS_work_M&E (TB/NTB)
12	(15b/d) P_SS_work_fin (TB/NTB)	(15b/d) P_SS_work_fin (TB/NTB)

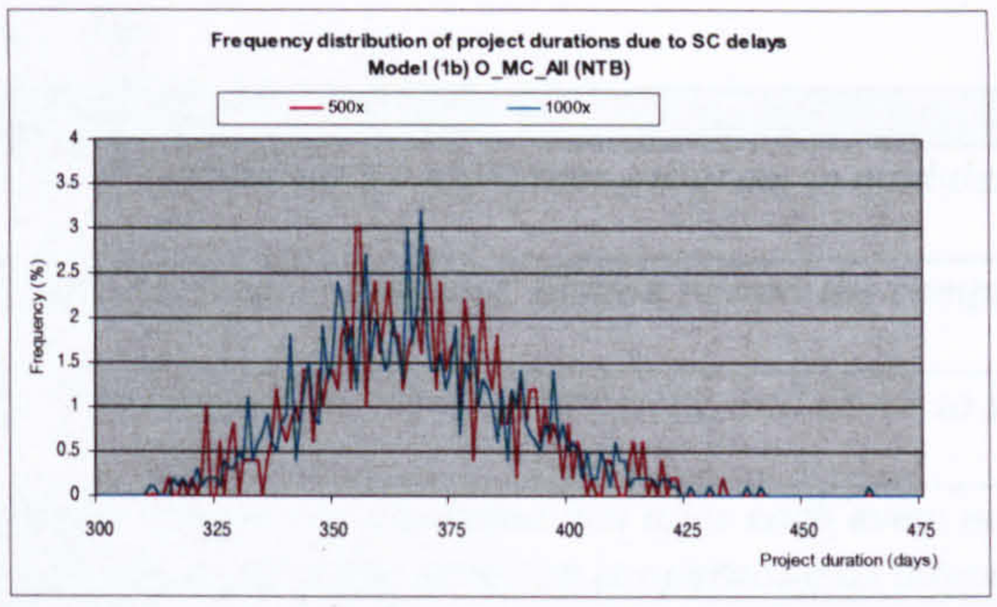
5.3.3 Defining the number of iterations

Once the models were ready to run, there was a question to answer as to how many times they should be run to get the optimum result. A parameter that can be used here is the convergence of the result of the simulations. At some point, the output will begin to converge to such an extent that the result is only changing by a small percentage. When the output from the simulations begins to converge, the mean project duration does not change significantly for that number of consecutive iterations. Model (1b) O_MC_All (NTB) was used for the trials to determine the right number of iterations.

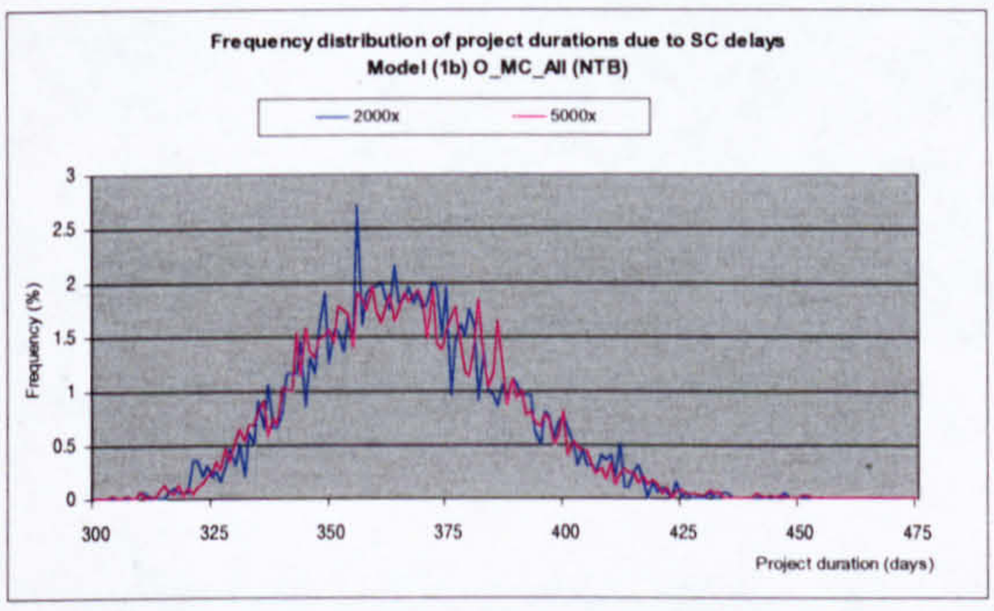
For the first trials, the model was run with a low number of simulation (100 times). The result was not satisfactory as it did not converge. This was indicated by the graph showing the frequency distribution of the project durations which was very spiky, as shown in figure 5-12a below. The number of iterations was then increased to 300. At this point, although the project durations converged with less than 1% variation, the graph was still spiky. When the number of simulations was increased to 1000, the graph became smoother, but was still spiky (figure 5-12b). As the number of simulations was increased to 20000 times, the graphs became much smoother (figure 5-12d). It was expected that the smoother the graphs, the more confidence could be placed in the results. With 20000 iterations, the results converged with less than 0.01% variation. This level of convergence is more than adequate, as with such low variation, it can be said that the mean project duration effectively remains constant for 20000 consecutive iterations. It was then concluded that simulating the model 20000 times was satisfactory and the results could be used for further analysis.



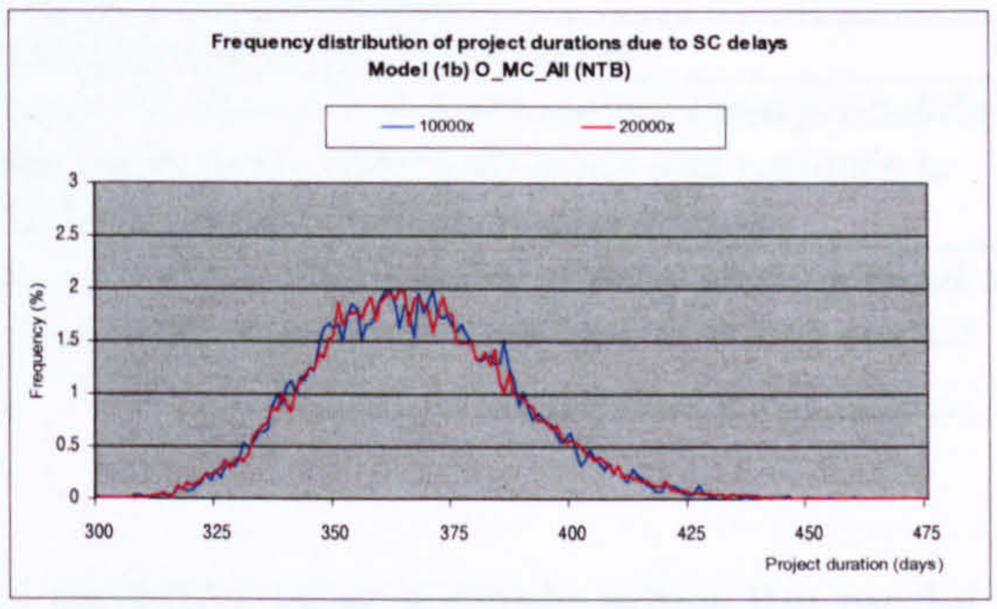
(a)



(b)



(c)



(d)

Figure 5-12 Trials of number of iterations

5.4 Model verification and validation

There is a major concern about using simulation as a tool in problem solving and decision making, that revolves around whether the model is accurate and its results are correct. This concern can be addressed through model verification and validation. Law and Kelton (2000) define verification as the process of determining *"whether the conceptual simulation model (model assumptions) has been correctly translated into a computer program"*. Validation is defined as *"the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model"* (AIAA, 1998). They will be explained in more detail below.

5.4.1 Model verification

Verification is concerned with building the model correctly. It is basically carried out by debugging the simulation computer program to ensure that the conceptual model is implemented correctly in the computer and checking to ensure the input parameters and logical structure of the model are correctly represented. Debugging a large-scale simulation program, however, can be a difficult and strenuous task due to a potentially large number of logical paths in the program.

Some techniques for verification are proposed by Law and Kelton (2000), as shown in table 5-7 below.

Table 5-7 Verification techniques (Law and Kelton, 2000)

Technique	Description
Technique 1	*In developing a simulation model, write and debug the computer program in modules or subprograms.*
Technique 2	*In developing large simulation models, have more than one person review the computer program.*
Technique 3	*Run the simulation under a variety of settings of the input parameters, and check to see that output is reasonable.*
Technique 4	*Use 'trace' where the state of simulated system are displayed just after each event occurs and are compared with hand calculations to see if the program is operating as intended.*
Technique 5	*The model should be run, when possible, under simplifying assumptions for which its true characteristics are known or can easily be computed.*
Technique 6	*It may be helpful to observe an animation of the simulation output.*
Technique 7	*Compute the sample mean and sample variance for each simulation input probability distribution, and compare them with the desired (historical) mean and variance to suggest that values are being correctly generated from these distributions.*
Technique 8	*Use a commercial simulation package to reduce the amount of programming required. Care must be taken, however, when using a recently released one, as it may contain errors of a subtle nature.*

Verification techniques number 1 to 7 are probably most suitable when the model is develop using general-purpose or higher level programming language, such as FORTRAN, PASCAL, C, C++, as these techniques involve reviews of computer code, which are unlikely to be applicable when a commercial simulation package is used. Technique number 8, on the other hand, is clearly relevant when the model is developed using a commercial simulation package.

The use of a commercial simulation package as a verification technique is also recognised by Sargent (2003), who argues that the use of such a package will generally result in fewer errors and increase the probability of having a correct program. Also, programming time is usually reduced significantly when compared with the use of a higher level programming language. When a simulation language or package is used, the primary concern with verification is ensuring that an error free simulation program has been used, simulation language has been properly implemented on the computer, and the model has been programmed correctly in the simulation language.

For this research, Pertmaster Risk Expert™, special-purpose simulation software was used. As this is ready-to-use or special-purpose simulation software, its user does not need to spend time on programming, nor to deal with risks of program errors. Besides, it is also not possible to examine the code of the program as this is proprietary software or closed-source software. In addition, this program is version 7.82, which means that it has been enhanced and undergone debugging processes since version 1.0, thus the program is arguably reliable and program errors are likely to be minimal. Based on the arguments mentioned above, it can be said that the need for verification of the program used in this research was fulfilled by the use of a recognised commercial package.

5.4.2 Model validation

Validation is concerned with building the right model and is used to determine that a model is an accurate representation of the real system. Law and Kelton (2000) argue that collecting high quality information and data on the system is one way of increasing model validity. The high quality data can be obtained by having conversations with subject-matter experts, observing the system, or referring to existing theory or relevant results from similar simulation studies. Conversations with subject-matter experts is essential, as a simulation model cannot be developed in isolation, but must be developed with people who are familiar with the system being modelled. Observations of the system enable data to be collected from it for use in building the model. Existing theory or relevant results from similar simulation studies are often useful during the process of building the model, hence they should be sought out and used, if possible.

The way in which data was collected for building the simulation models presented here, is in line with the arguments mentioned above. The information and data used for building the simulation models in this research was obtained from the preliminary study (particularly from the regular visits to building projects) and the main survey. From the regular visits, conversations with site managers and observations of the building sites, including site documents, allowed information and data regarding supply chain management practice and supply chain delays to be captured, and was later used for developing the simulation models. In addition, the CPM network, one of the vital components of the simulation models, was also obtained from one of the projects visited. It was prepared by a project planner who had more than 10 years experience in the construction industry. With such experience, it could be argued that the CPM network should be reliable and ought to be representative of the best/common practice in the industry, as the network should contain the typical activities, durations and logic for typical medium-sized building projects. The main survey, which was carried out by distributing questionnaires to practitioners in the construction industry, allowed data on supply chain delays to be collected. The types of delays, the probabilities and the extent of their impact on activities were analysed, summarised and used to build the simulation models. It can be argued that this data was adequate and reliable as it was obtained from experts, i.e. experienced site managers who had good knowledge of supply chain delays in their projects. The existing literature was also useful for developing the questionnaires for the main survey, as many examples of delays recognised in construction supply chains were available. All in all, it can be said that the ways in which data was collected for building simulation models in this research are comparable to the ways that high quality data should be obtained to increase the model validity, as suggested by Law and Kelton (2000) above.

Besides using high quality data, there are also other validation techniques, as proposed by Sargent (2003) in table 5-8 below. Among these techniques, three of them are considered relevant and were used in the model validation of this research. They are *animation, event validation* and *extreme condition tests*, which will be discussed as follows:

Table 5-8 Techniques of validation (Sargent, 2003)

Technique	Description
Animation	The model's operational behaviour is displayed graphically as the model moves through time. For example, the movements of parts through a factory during a simulation are shown graphically
Comparison to Other Models	Various results of the simulation model being validated are compared to results of other (valid) models. For example, (1) simple cases of a simulation model may be compared to known results of analytic modes, and (2) the simulation model may be compared to other simulation models that have been validated
Degenerate Tests	The degeneracy of the model's behaviour is tested by appropriate selection of values of the input and internal parameters. For example, does the average number in the queue of a single server continue to increase with respect to time when the arrival rate is larger than the service rate?
Event Validity	The "events" of occurrences of the simulation model are compared to those of the real system to determine if they are similar. An example of events is deaths in a fire department simulation
Extreme Condition Tests	The model structure and output should be plausible for any extreme and unlikely combination of levels of factors in the system. For example, if in-process inventories are zero, production output should be zero.
Face Validity	Face validity is asking people knowledgeable about the system whether the model and/or its behaviour are reasonable. This technique can be used in determining if the logic in the conceptual model is correct and if a model's input-output relationships are reasonable.
Historical Data Validation	If historical data exist (or if data are collected on a system for building or testing a model), part of the data is used to build the model and the remaining data are used to determine (test) whether the model behaves as the system does
Historical Methods	The three historical methods of validation are *rationalism*, *empiricism*, and *positive economics*. Rationalism assumes that everyone knows whether the underlying assumptions of a model are true. Logic deductions are used from these assumptions to develop the correct (valid) model. Empiricism requires every assumption and outcome to be empirically validated. Positive economics requires only that the model be able to predict the future and is not concerned with a model's assumptions or structure (causal relationships or mechanisms).
Internal Validity	Several replications (runs) of a stochastic model are made to determine the amount of (internal) stochastic variability in the model. A large amount of variability (lack of consistency) may cause the model's results to be questionable and if typical of the problem entity, may question the appropriateness of the policy or system being investigated.
Multistage Validation	A combination of three historical methods of rationalism, empiricism, and positive economics into a multistage process of validation. This validation method consists of (1) developing the model's assumptions on theory, observations, and general knowledge, (2) validating the model's assumptions where possible by empirically testing them, and (3) comparing (testing) the input-output relationships of the model to the real system.
Operational Graphics	Values of various performance measures, e.g., the number in queue and percentage of servers busy, are shown graphically as the model runs through time; i.e., the dynamical behaviours of performance indicators are visually displayed as the simulation model runs through time to ensure they are correct.
Parameter Variability-Sensitivity Analysis	This technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behaviour or output. The same relationships should occur in the model as in the real system. Those parameters that are sensitive, i.e., cause significant changes in the model's behaviour or output, should be made sufficiently accurate prior to using the model. (This may require iterations in model development.)
Predictive Validation	The model is used to predict the system's behaviour, and then comparison are made between the system's behaviour and the model's forecast to determine if they are the same. The system data may come from an operational system or be obtained by

Technique	Description
	conducting experiments on the system, e.g., field tests.
Traces	The behaviour of different types of specific entities in the model is traced through the model to determine if the model's logic is correct and if the necessary accuracy is obtained.

5.4.2.1 Animation

Animation allows the model's operational behaviour to be displayed graphically as the model moves through time. For example, movements of parts through a factory can be displayed during a simulation. As for Pertmaster Risk Expert™ used in this research, it can graphically display the operational behaviour of the model. It can display how the activities in the network are affected when the supply chain delays occur with varying extents of delay. Through animation, the links connecting activities and delays can also be checked thoroughly to make sure there are no broken links in the model. There is also an option to simulate the model step by step, which is very useful to ensure that the model behaves as intended.

5.4.2.2 Event Validation

In *event validation*, events in the simulation model are compared to those of the real system to determine if they are similar. In the real system, delays might occur prior to or during an activity. In this research, this was modelled in the network by positioning the delays as preceding or succeeding the activity. To measure the total duration of the activity including the delays, a summary activity (hammock) was used. To anticipate various combinations of these delays in the real system, they were modelled either in series or in parallel to represent the optimistic and pessimistic scenarios. The modelling of these delays was tested and proven to be able to represent events in the real system. The details of this modelling can be found in sections 5.1.4 and 5.1.5.

How the time buffers were modelled in this research and the use of probabilistic branches are also good examples of event validation (see sections 5.1.6 and 5.1.7). It was understood that when time buffers were added to an activity, delays could be absorbed partially or wholly by the time buffers, so that the activity might or might not be delayed. The use of probabilistic branches was able to anticipate a certain combination of delays which precedes the late delivery of materials delay. It was shown that the way these were modelled was able to mimic events in the real system.

5.4.2.3 Extreme Condition Tests

In this test, the model structure and output should be reliable for any extreme and unlikely combination of levels of factors in the system. Zero in-process inventories should result in zero output of production, for example.

For this research, a simple test was carried out to ensure that the model was correct for extreme conditions. It was understood that the deterministic duration of the project is 300 days. This means that when no delays are applied to the model, the project duration should be the same as the deterministic duration. This was tested on each

model and the results showed that when no delays at all were applied to the model, the project duration was the same as the deterministic duration.

Chapter 6
Analysis and Discussion of the Results

This chapter presents the results obtained from the various simulation models. It consists of 5 main sections, as follows:

6.1 **The nature of the network with SC delays**: This section reveals the characteristics of the CPM network with the delays, including the paths through the network, the criticality and sensitivity of the activities, and the distribution of the delays in various models.

6.2 **How the results are presented**: This section shows how the results of the simulations are presented in different forms so that they can be understood more easily.

6.3 **Comparing the optimistic and the pessimistic versions**: The results from the optimistic and the pessimistic models are compared using both analytical and statistical analysis.

6.4 **The provision of time buffers**: The impact of providing time buffers on material delivery and their implications to the project is discussed in this section

6.5 **Results of the simulations**: This section presents and discusses the results of the simulation of the various scenarios, including the implications of the results.

6.1 The nature of the CPM network with SC delays

There are different ways of viewing the CPM network simulated with the various combinations of supply chain delays and it is considered important at this stage for the reader to gain a good appreciation of the models. They can be understood either by looking at how the various delays affect the paths through the networks, by examining the criticality and sensitivity of activities on the network, or by seeing how the delays are distributed on activities along the network. Each of these will now be considered in turn.

6.1.1 The paths through the network

It was mentioned in section 5.1.2 that the CPM network used for the simulation has 9 paths, two of which (paths 3 and 7, see table 6-1) are critical. The rest, which are non critical, may become critical at any time during the simulation if the total delays on the activities which share the total float exceed the available total float in the

network. To examine how these non-critical paths may become critical, models (1b)O_MC_All (NTB) and (11b)SS_All (NTB) that have the maximum number of delays were used. These were chosen to represent models where all work was carried out by the main contractor and where subcontractors were used in the project.

Table 6-1 columns (b) and (c) below show the 9 possible paths through the network and the total float available on each path. The total float on each path is shared by a number of activities (column (d)). These activities can potentially be affected by delays during the simulation. If the total delays occurring on these activities exceed the total float available, the project will be delayed as a result. Columns (e) and (f) show the total maximum delay duration that can potentially impact on these activities in both models. The result of the comparisons of total float available and total delays is shown in column (g). It can be seen that there are some non-critical paths which can become critical because the total delays exceed the total float available in the network. This can happen in paths 1, 2, 4, 5, 6 and 8 of model (1b)O_MC_All (NTB) and paths 2, 4, 6 and 8 of model (11b)SS_All (NTB). In addition, there are also some paths that will never be critical, because the total delays will never exceed the total float available, as shown in path 9 of model (1b)O_MC_All (NTB) and paths 1, 5 and 9 of model (11b)SS_All (NTB). For the other models not shown here, in general, the number of delays which may impact on each activity is less than for these two models, giving less potential delays on each activity, as well as on the project as a whole (see appendix C1). As these models have different delays associated with each activity, the potential criticality of the nine paths on the network during the simulations may be slightly different from the two models above.

Identifying the various paths through the network and understanding how these may change from non critical to critical is seen as helpful in understanding one aspect of the nature of the network being used.

Table 6-1 Various paths through the CPM network, Total Floats and potential delays

Paths	Activities	Total Float (TF)	Activities which share the total float	Total max delay duration that can potentially impact on activities in column (d)		Conclusion
(a)	(b)	(c)	(d)	(e) (1b)O_MC_All (NTB)	(f) (11b)SS_All (NTB)	(g)
1	1*-2-3-4-5-6-7-8-10-11-12-13-18-19-21-22-23-24-25-26*	46 days	12, 13	125 days**	45 days	TF< Delay (e), TF>Delay (f) Can be critical on (1b) O_MC_All (NTB), but will never be critical on (11b) SS_All (NTB)
2	1*-2-3-4-5-6-7-8-10-11-14-15-16-17-18-19-21-22-23-24-25-26*	5 days	16, 17	71 days	44 days	TF< Delay Can be critical
3	**1*-2-3-4-5-6-7-8-10-11-14-15-20-18-19-21-22-23-24-25-26***	**0 day**	-	-	-	TF=0 Critical
4	1*-2-3-4-5-6-7-8-10-11-14-15-27-28-29-30-31-22-23-24-25-26*	17 days	27,28,29,30,31	101 days	85 days	TF< Delay Can be critical
5	1*-2-3-4-5-6-7-8-9-10-11-12-13-18-19-21-22-23-24-25-26*	46 days	12, 13	125 days**	45 days	TF< Delay (e), TF>Delay (f) Can be critical on (1b) O_MC_All (NTB), but will never be critical on (11b) O_MC_All (NTB)
6	1*-2-3-4-5-6-7-8-9-10-11-14-15-16-17-18-19-21-22-23-24-25-26*	5 days	16, 17	71 days	44 days	TF< Delay Can be critical
7	**1*-2-3-4-5-6-7-8-9-10-11-14-15-20-18-19-21-22-23-24-25-26***	**0 day**	-	-	-	TF=0 Critical
8	1*-2-3-4-5-6-7-8-9-10-11-14-15-27-28-29-30-31-22-23-24-25-26*	17 days	27,28,29,30,31	101 days	85 days	TF< Delay Can be critical
9	1*-2-3-32-33-34-35-25-26*	185 days	32,33,34,35	102 days	102 days	TF>Delay Will never be critical

Note:
- Activities number 1* and 26* are milestones (Start and Finish).
- 125 days** are obtained by summing up the maximum delays that can impact activity 12 and activity 13, i.e. 39 and 86 days

6.1.2 Criticality and sensitivity of the activities

Another way of understanding the nature of the CPM network is by looking at how critical and how sensitive activities on the network are. The criticality index (CI) and duration sensitivity (DS) may be used for this purpose. The criticality index allows activities that are likely to cause delays to the project to be identified. It is defined as the percentage of time an activity appears on the critical path during the simulations. If an activity has a 100% criticality index, it means that during the simulation this activity was always on the critical path. On the other hand, activities with a low or zero criticality index are much less likely to cause a delay to the project finish date.

It should be noted that an activity with 100% criticality index does not necessarily mean that it has a significant impact on the project duration, as an activity with only 1 day duration, for example, can also have 100% criticality index. To deal with this problem, duration sensitivity can be used, which gives an indication of how much each activity affects the project, by measuring the correlation between the duration of an activity including associated delays and the duration of the project. This means it can be used to identify activities that are most likely to cause delay to the project.

Duration sensitivity is calculated after the simulation is complete using the Pearson's Product Moment formula. This formula calculates the correlation (r) of two set values, i.e. the duration of the project and the particular activity, as follows:

$$r = \left[\frac{\frac{\Sigma(x-\bar{x})(y-\bar{y})}{n-1}}{\sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}\sqrt{\frac{\Sigma(y-\bar{y})^2}{n-1}}} \right] \text{ x } 100\%$$

where:

r = correlation
x = value from first data set (project duration)
y = value from second data set (activity duration)
n = number of simulations

Figures 6-1 and 6-2 below show the criticality of the original critical path, the criticality index and the duration sensitivity of models (1b) O_MC_All (NTB) and (11b) SS_All (NTB). It can be seen that for both models, 43% of activities (15 out of 33) are always critical, 36% (12 out of 33) may sometimes be critical and 18% (6 out of 33) are never critical.[3] It can also be said that 82% (43% + 39%) of activities have opportunities to be critical with various degrees of criticality and impact on project completion. The rest, 18% will never be critical and have no impact on project completion.

---

[3] Note: Activities 1 (Start) and 26 (Finish) are milestones, hence discounted.

With regard to duration sensitivity, most activities have values between 0% and 25%. It is clear from this that there is no particular activity which has a very strong correlation with project duration. This can be interpreted as meaning that there is no activity which dominates the behaviour of the project, as most activities have a relatively low degree of sensitivity.

To sum up, activities on both models have various degrees of criticality and relatively low sensitivity. It is clear that the majority of the activities on the original critical path were critical for all of the simulations, with only 5 activities not in this category, and 3 of these had criticality indices of 96%. Most activities were also found to have some opportunity to impact on the project.

For the other models not shown here, the criticality index and the duration sensitivity are not significantly different from the two models above (see appendix C2). In general, the majority of the activities on the original critical path were critical for all of the simulations with relatively low sensitivity, meaning that most activities have some opportunity to impact on the project.

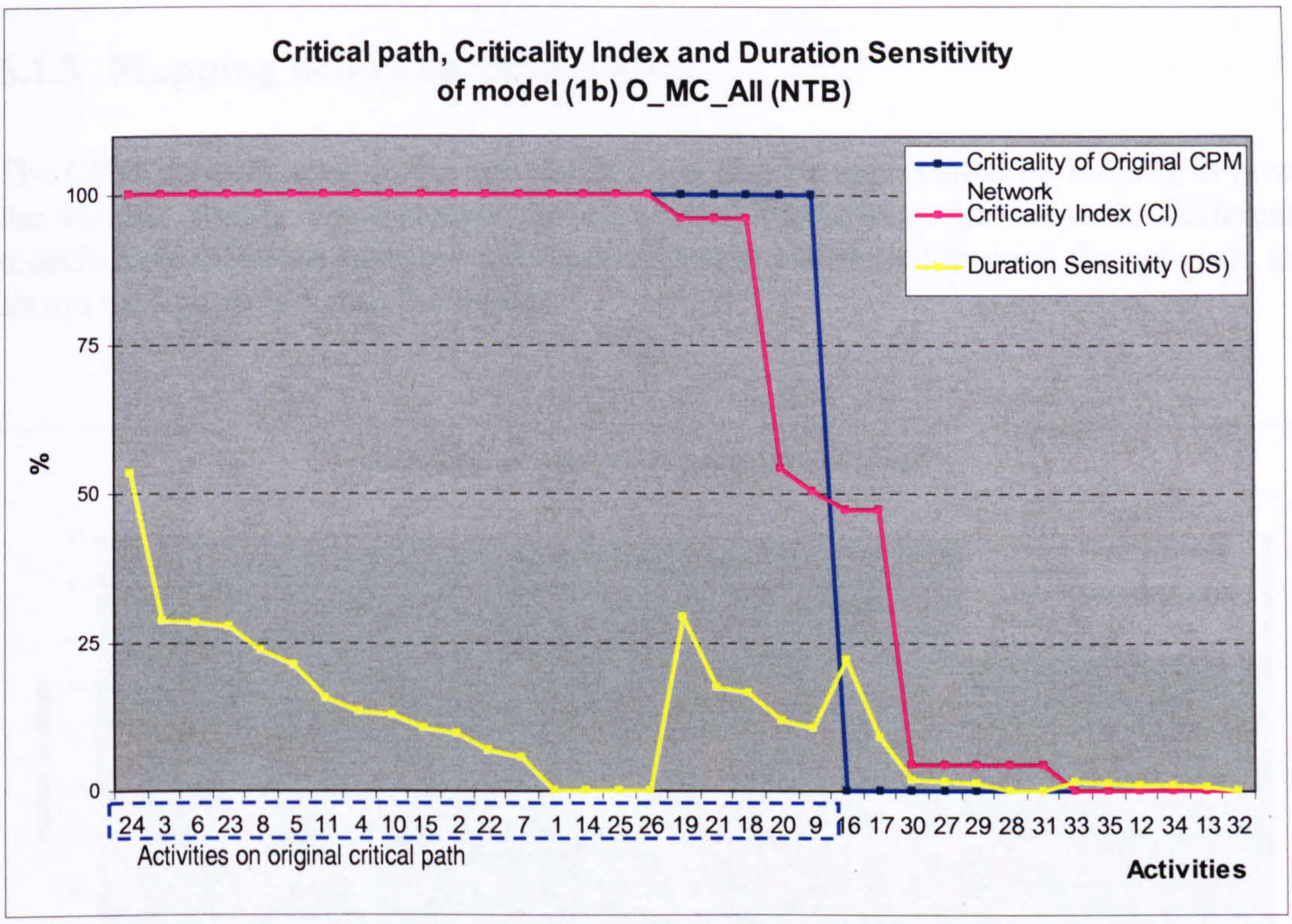


Figure 6-1 Critical path, criticality index and duration sensitivity of model (1b) O_MC_All (NTB)

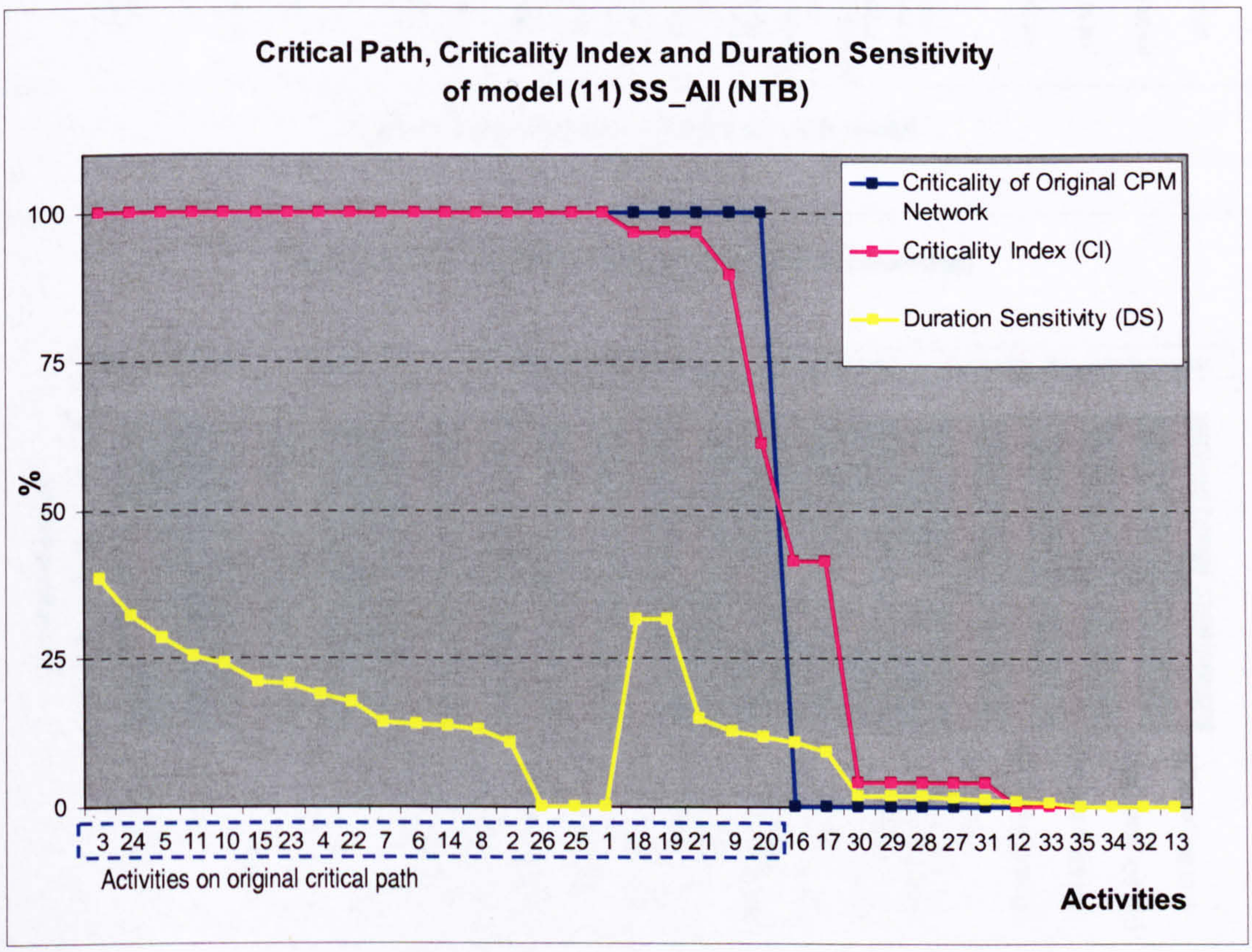


Figure 6-2 Critical path, criticality index and duration sensitivity of model (11b) SS_All (NTB)

6.1.3 Mapping delays on the network

The CPM network used in the simulations can also be appreciated by looking at how the various supply chain delays are distributed throughout the network. Different models have different numbers and types of delays distributed through the network, as shown by figures 6-3 and 6-4 below.

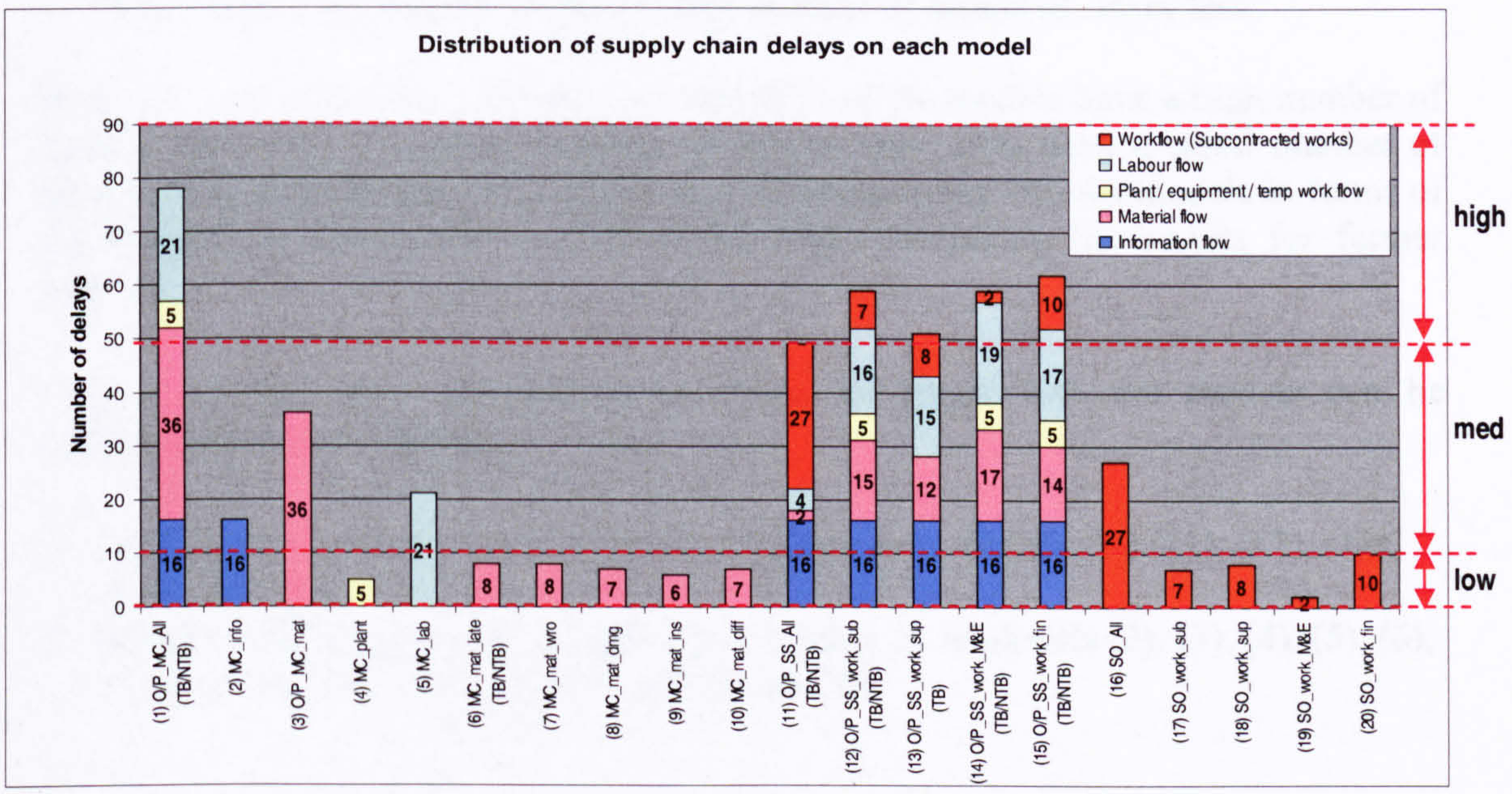


Figure 6-3 Distribution of delays on each model

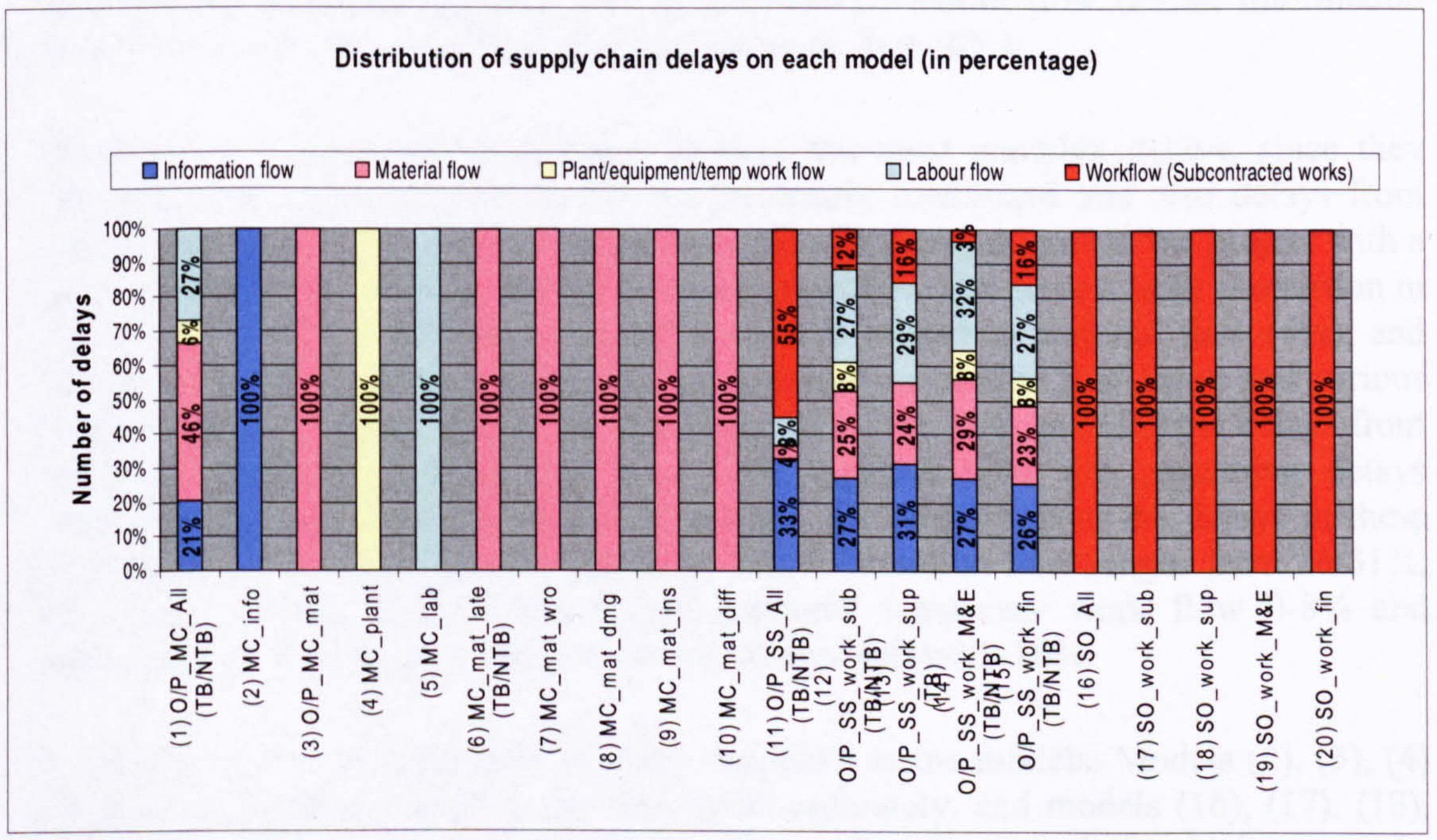


Figure 6-4 Distribution of delays on each model in percentage

Figure 6-3 shows that the maximum number of delays is 78, in model (1), and the minimum is 2, in model (19). Based on the number of delays, the models can be classified into three categories, as follows:

1. Models with a high number of delays, as in models (1), (11), (12), (13), (14), (15) which have a total number of delays of 49 or more.
2. Models with a medium number of delays, as in models (2), (3), (5), (16) which have a total number of delays between 10 and 49.
3. Models with a small number of delays, as in models (4), (6), (7), (8), (9), (10), (17), (18), (19), (20) which have a total number of delays of 10 or less.

From this classification, it can be seen that 30% of the models have a high number of delays, 20% have a medium number of delays, and 50% have a small number of delays. This classification is a simple way of categorising various models in terms of the number of delays and will be useful when comparing the results for further analysis.

Concerning the delay distribution as shown in figure 6-4, the models can be categorised into two groups:

A. Models which have a number types of delays, as in models (1), (11), (12), (13), (14), and (15).
B. Models which apply only a single type of delay, as in models (2), (3), (4), (5), (6), (7), (8), (9), (10), (16), (17), (18), (19) and (20).

In group A, model (1) has delays from the four flows, i.e. information flow, material flow, plant/equipment/ temporary work flow and labour flow. In this model, material flow has the highest proportion (46%), followed by labour flow (27%), information flow (21%) and plant/ equipment/temporary work flow (6%).

Models (11), (12), (13), (14) and (15) have the most complex delays, since they incorporate delays from the four flows previously mentioned and also delays from subcontractors. In model (11), delays from subcontractors dominate the project with a proportion of 55%. Delays related to information flow also have a large proportion in this model of 33%. The rest is shared by delays related to material flow (4%), and labour flow (8%). While model (11) applies delays from the four flows and various subcontractors' delays all at once, in models (12), (13), (14) and (15) the delays from subcontractors are applied one at a time together with the remaining delays attributable to the main contractor. In general, the proportion of the delays in these four models is not significantly different. The information flow ranges from 26-31%, the material flow 23-29%, the plant/equipment/ temporary work flow 0-8% and labour flow 27-32% and workflow (subcontractor delays) 3-16%.

In group B, only a single type of delay is applied to the models. Models (2), (3), (4) and (5) incorporate delays of the four flows separately, and models (16), (17), (18), (19) and (20) apply only individual delays from subcontractors. It should, however, be noted that in models (3) and (16), the single type of delays, which relate to material flow and subcontractors can be broken down further into more specific types of

delays. While in model (3) the various delays in material flow are applied all at once, models (6), (7), (8), (9) and (10) apply particular delays in material flow separately. Also, while model (16) applies only subcontractors delays, but all at once, models (17), (18), (19) and (20) apply the subcontractor delays one at a time.

All in all, the delay distribution throughout the networks is one of the important aspects that should be considered when comparing the results of simulations. It allows us to understand how the results of simulations of the various models have been achieved. Hence, knowing how the delays are distributed within the various models is essential for the analysis.

The delay distributions as shown in figures 6-3 and 6-4 above, show how different numbers and types of delays are distributed through the network. However, they do not show the proportion of the delays that are on the critical and non critical paths. Knowing how delays are distributed on the critical and non critical paths is also essential for understanding the results of the various simulations.

Figures 6-5 and 6-6 below show the proportion of delays on the original critical and non critical paths. It can be seen that the majority of models have more than 60% of their delays on the critical path. Clearly, delays on the critical path will be more likely to cause delay to the project than those on non critical paths. Although it is possible that delays on non critical paths may become critical and may cause delay to the project, the criticality index in section 6.1.2 shows that the majority of the activities on the original critical path were critical for all of the simulations. This means that for the typical CPM network used for this simulation, delays on the original critical path are likely to determine whether or not the project will be delayed.

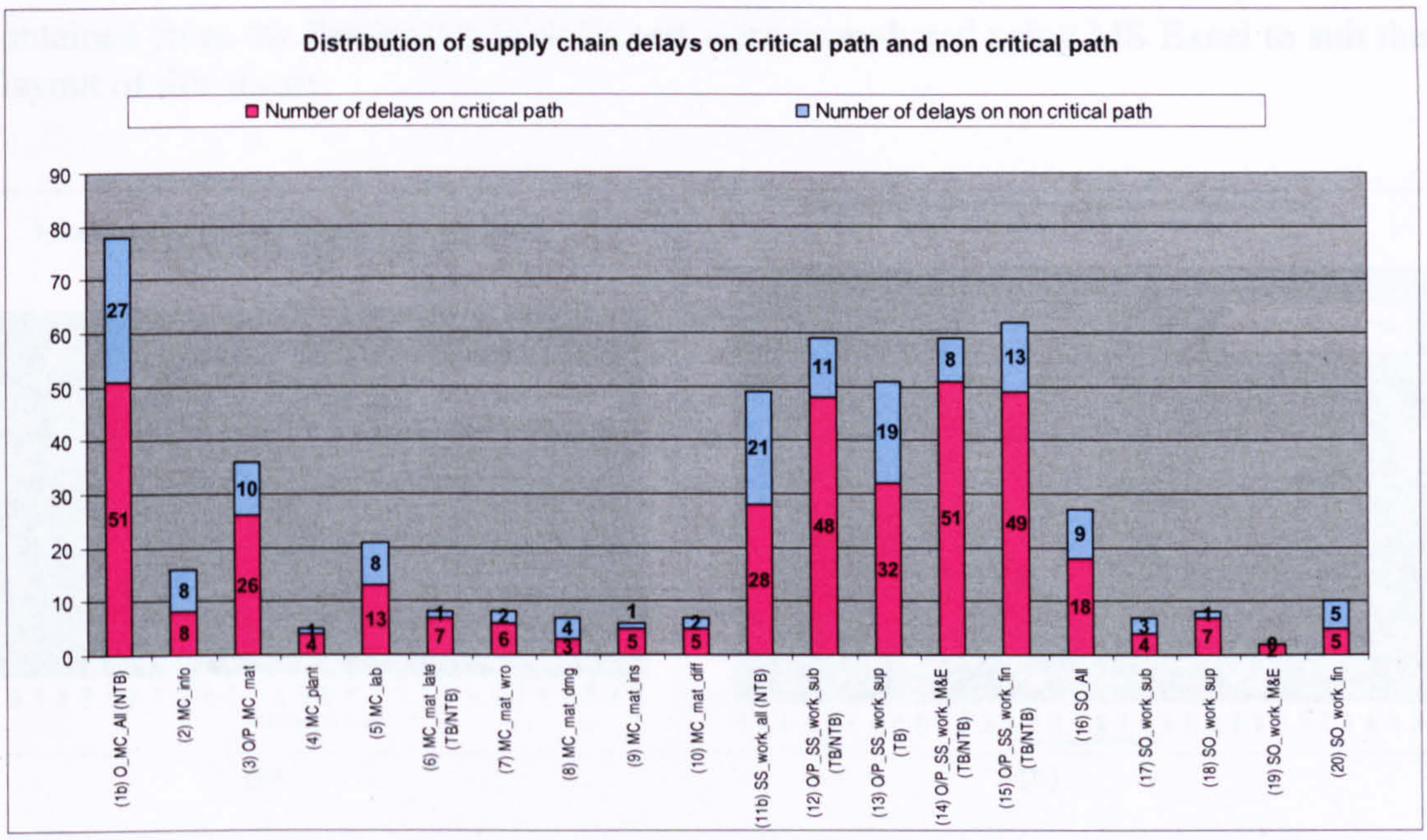


Figure 6-5 Distribution of delays on the critical and non critical paths

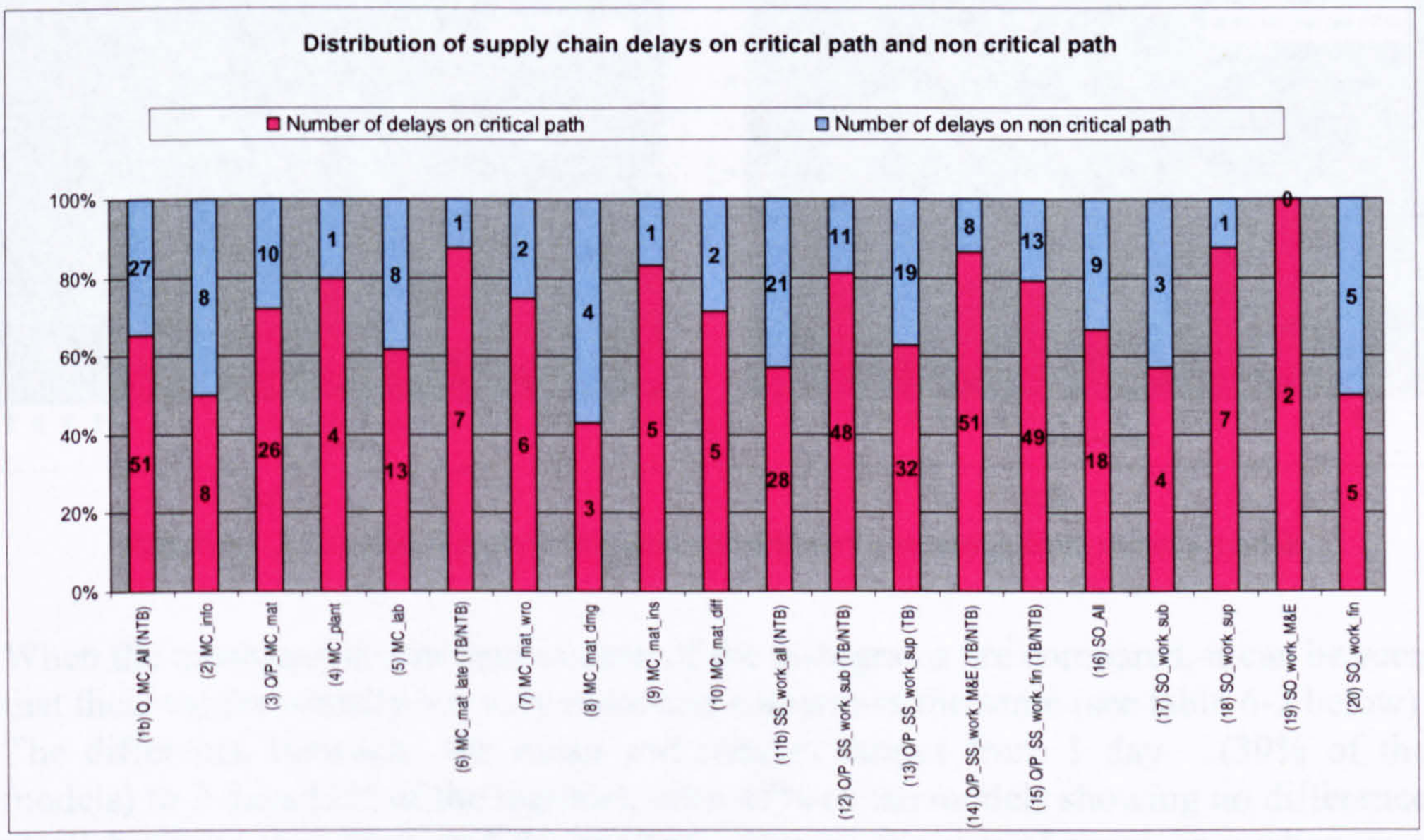
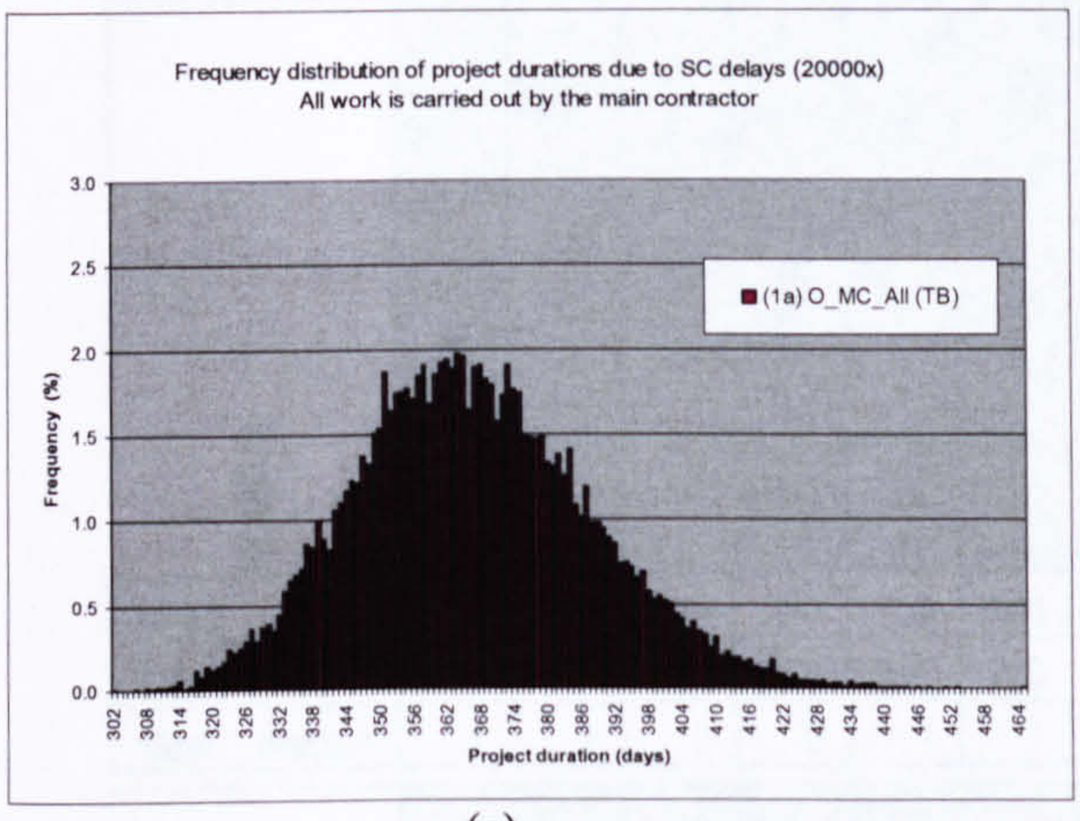


Figure 6-6 Distribution of delays on the critical and non critical paths shown as percentages

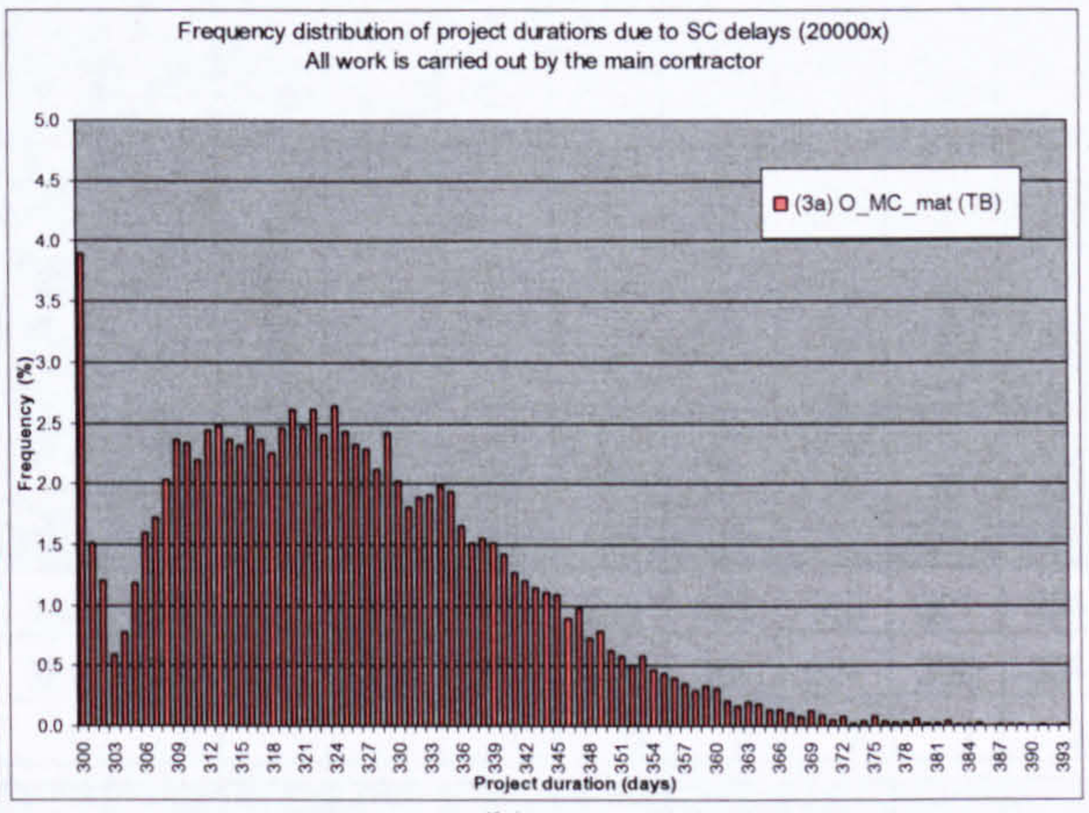
6.2 How the results are presented

Figure 6-7 below shows examples of typical frequency distributions of project durations resulting from simulations of various models. They were chosen based on their shapes that are representative of most of the histograms produced. Figure 6-7a represents typical histograms that look normally distributed as indicated by the symmetrical bell-shape, while the other three (figure 6-7b, c and d) represent those which are very unlikely to follow a normal distribution. The complete histograms for all models can be seen in appendix C3. It should be noted that all the histograms

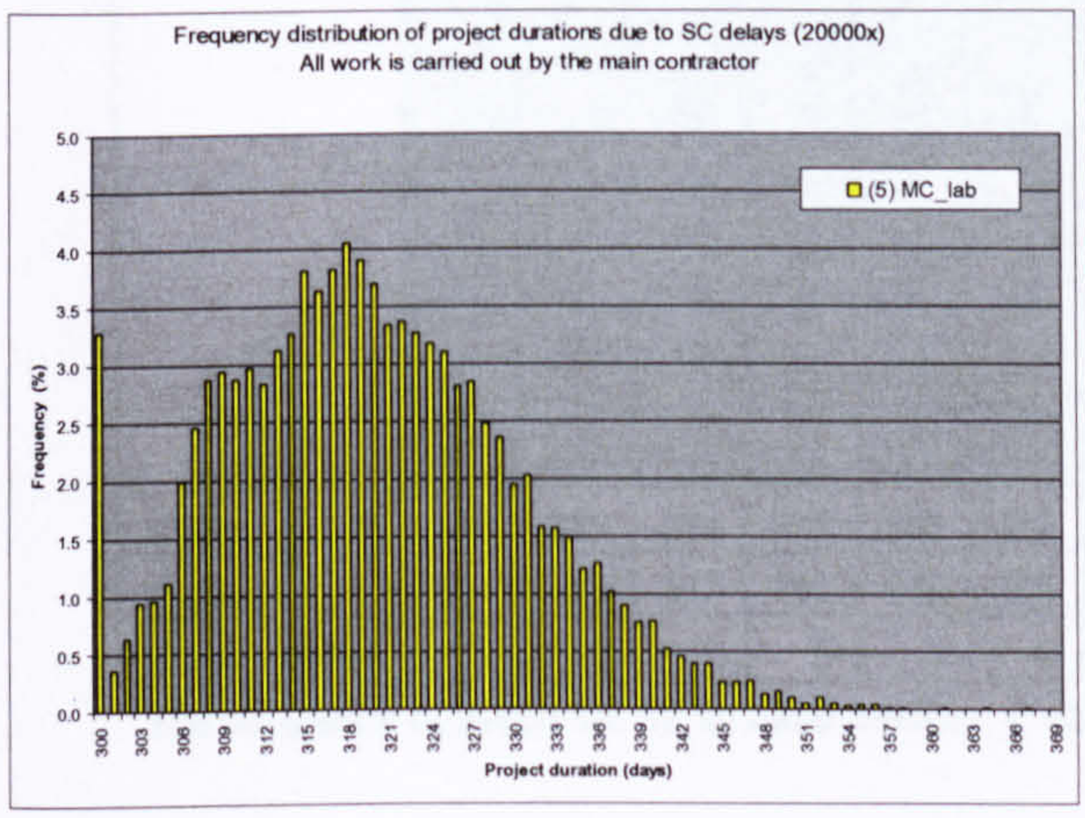
obtained from the Pertmaster Risk Expert were reproduced using MS Excel to suit the layout of this thesis.



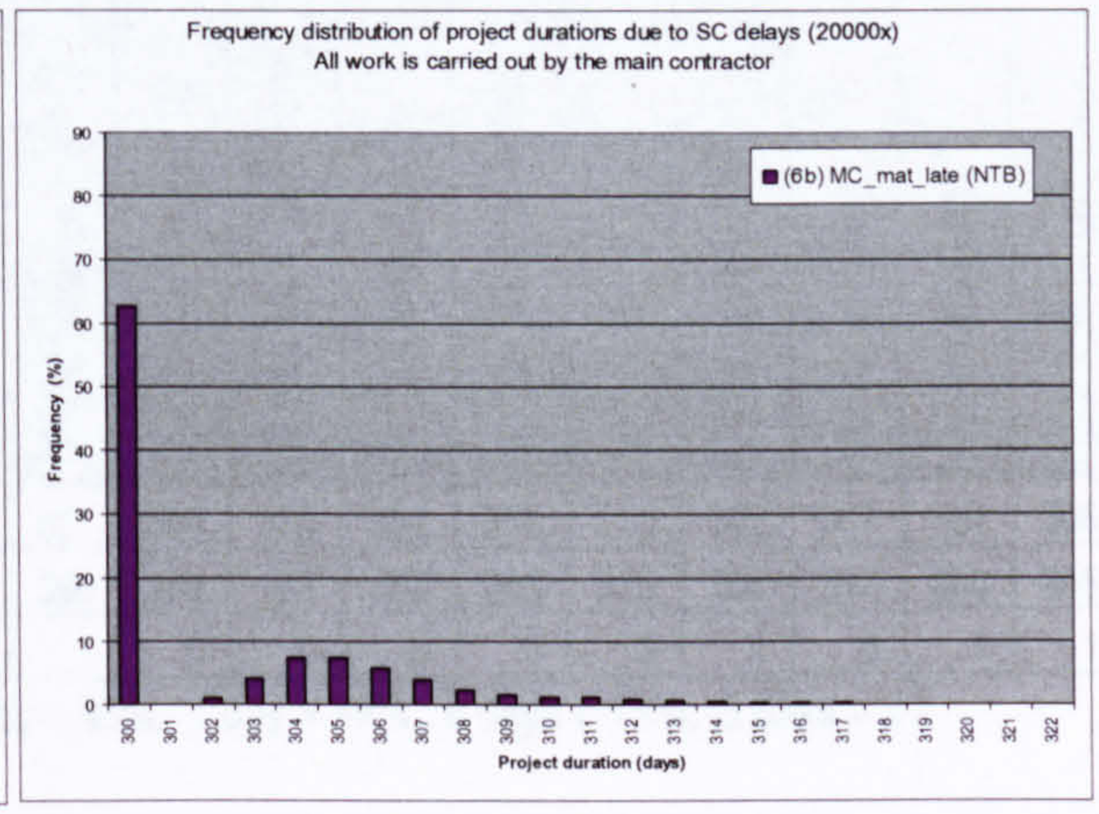
(a)



(b)



(c)



(d)

Figure 6-7 Examples of typical frequency distributions resulting from various models

When the mean and the median of each of the histograms are compared, it can be seen that their values actually are very close and sometimes the same (see table 6-2 below). The difference between the mean and median ranges from 1 day (39% of the models) to 3 days (3% of the models), with 45% of the models showing no difference at all between the mean and the median. Hence, the use of mean or median as a measure of central tendency will actually not make much difference. A decision was thus taken to use the median as the measure of central tendency of all the distributions, because the median can represent the skewed histograms better than the mean.

Table 6-2 Comparison of mean and median of each histogram

MODELS	(1a) O_MC_All (TB)	(1b) O_MC_All (NTB)	(1c) P_MC_All (TB)	(1d) P_MC_All (NTB)	(2) MC_info	(3a) O_MC_mat (TB)	(3b) O_MC_mat (NTB)	(3c) P_MC_mat (TB)	(3d) P_MC_mat (NTB)	(4) MC_plant	(5) MC_lab	(6a) MC_mat_late (TB)	(6b) MC_mat_late (NTB)	(7) MC_mat_wro	(8) MC_mat_dmg	(9) MC_mat_ins
Mean:	366	368	369	370	318	324	326	323	324	304	319	300	302	303	301	304
Median:	365	367	369	370	317	323	325	322	323	305	319	300	300	301	300	301
Mean - median	1	1	0	0	1	1	1	1	1	-1	0	0	2	2	1	3

MODELS	(10) MC_mat_diff	(11a) O/P_SS_All (TB)	(11b) O/P_SS_All (NTB)	(12a) SS_work_sub (TB)	(12b) SS_work_sub (NTB)	(13a) SS_work_sup (TB)	(13b) SS_work_sup (NTB)	(14a) SS_work_M&E (TB)	(14b) SS_work_M&E (NTB)	(15a) SS_work_fin (TB)	(15b) SS_work_fin (NTB)	(16) SO_All	(17) SO_work_sub	(18) SO_work_sup	(19) SO_work_M&E	(20) SO_work_fin
Mean:	316	338	338	367	368	350	351	364	365	352	353	315	302	307	301	306
Median:	314	338	337	367	368	350	350	364	365	352	353	315	300	307	300	305
Mean - median	2	0	1	0	0	0	1	0	0	0	0	0	2	0	1	1

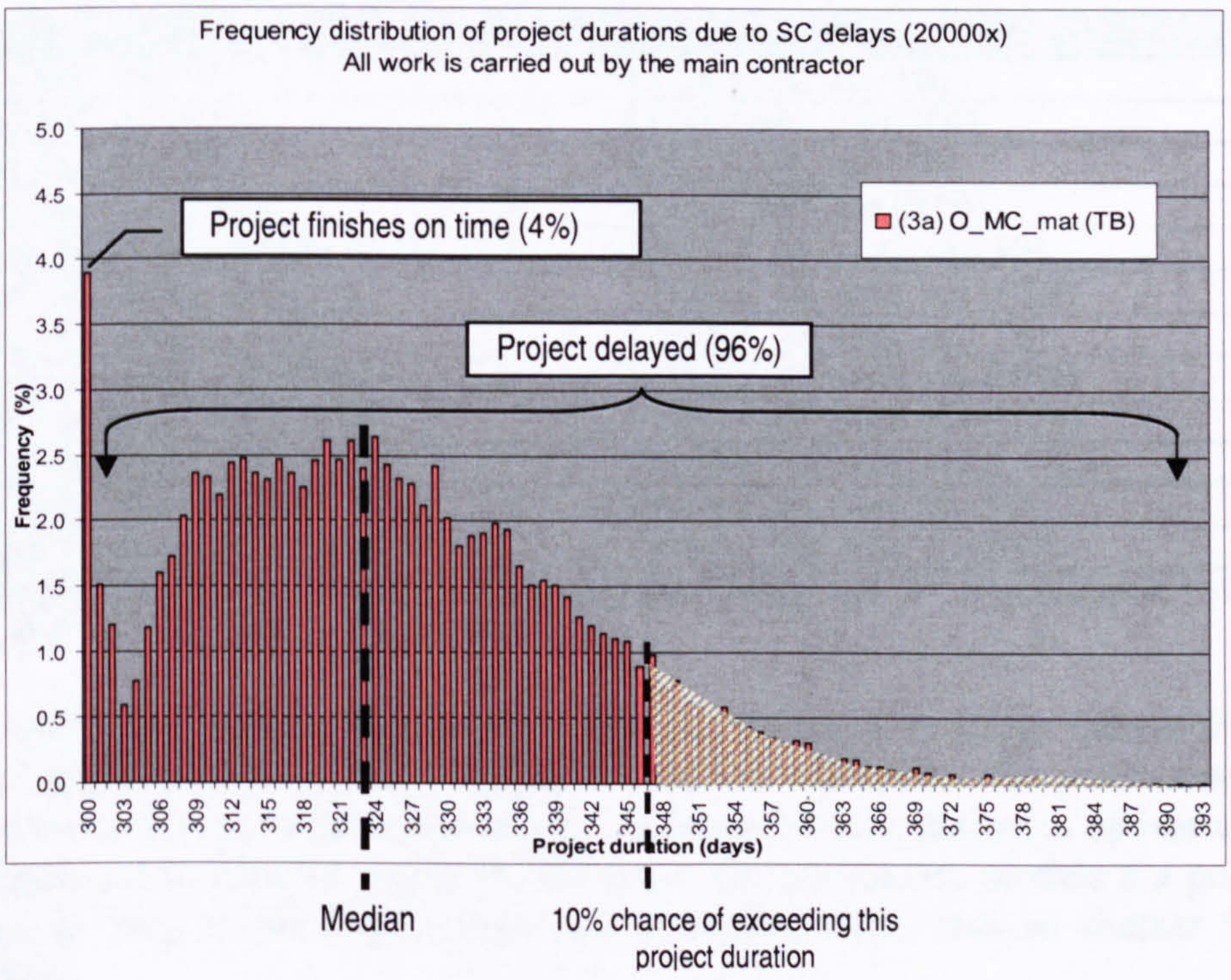
The difference between the means and median; 0 day = 45%, 1 day = 39%, 2 days = 13%, 3 days = 3%

Comparing the typical histograms shown in figure 6-7, it can be seen that figure 6-7b, c and d all have relatively high frequencies for a project duration of 300 days which then drop sharply. It should be noted that 300 days is the minimum project duration and relates to a project which is not delayed by supply chain delays at all.

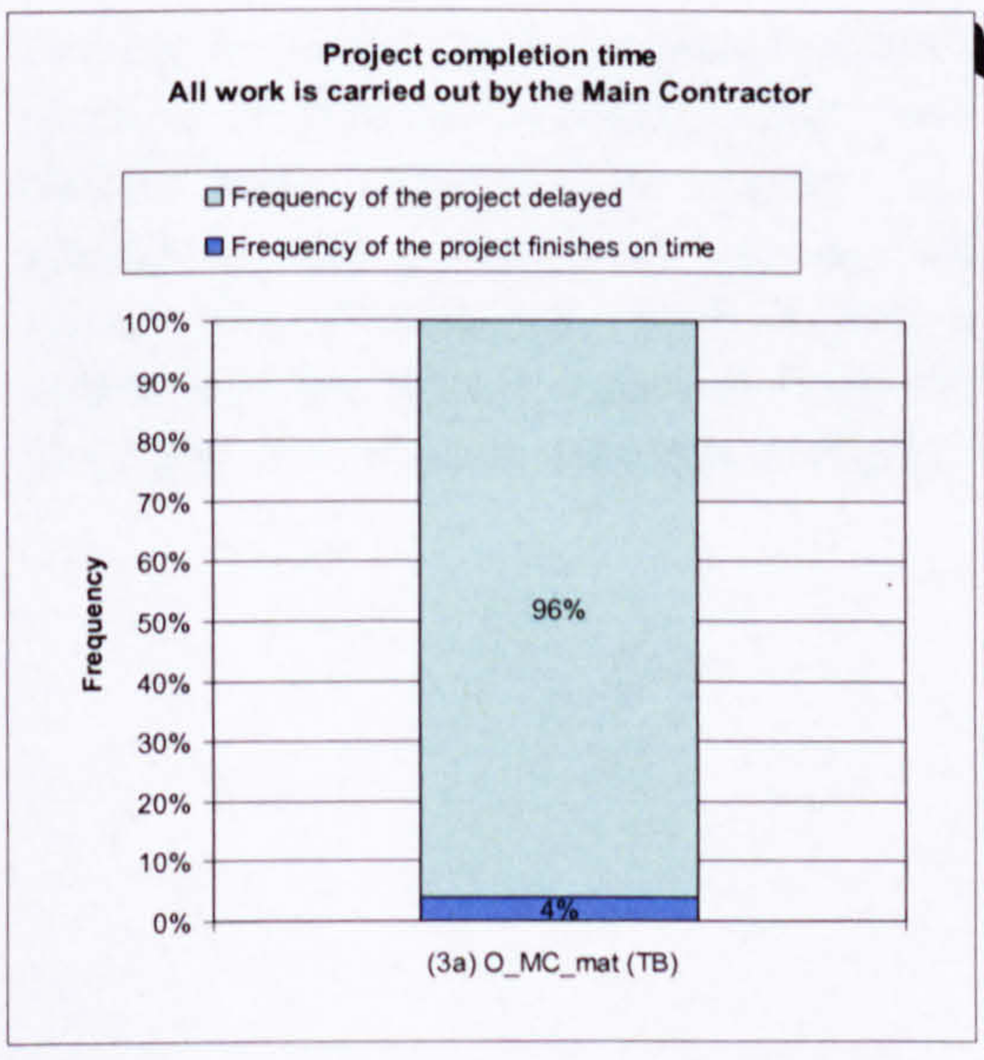
To understand the results of the simulations better, the typical histograms above can be shown in two main graphs as shown in figure 6-8 below. A histogram from figure 6-7b has been selected for illustration purposes (shown here as in figure 6-8a). Figure 6-8b shows the frequencies of projects that finish on time and those that are delayed, and figure 6-8c shows the extent of the delays. It can be seen in figure 6-8b that the frequency with which the project finishes on time is 4% and the frequency with which the project is delayed 96% (rounded to the nearest integer). This information is important for recognising how often problems along the supply chain can impact the project. The more often a project is delayed, the more attention should be paid to the particular factors that have caused the delay.

As was explained above, the median was chosen to represent the distribution, however, a single parameter is considered insufficient to represent the distribution. To give an idea of how this single duration can actually vary, the duration with a 10%

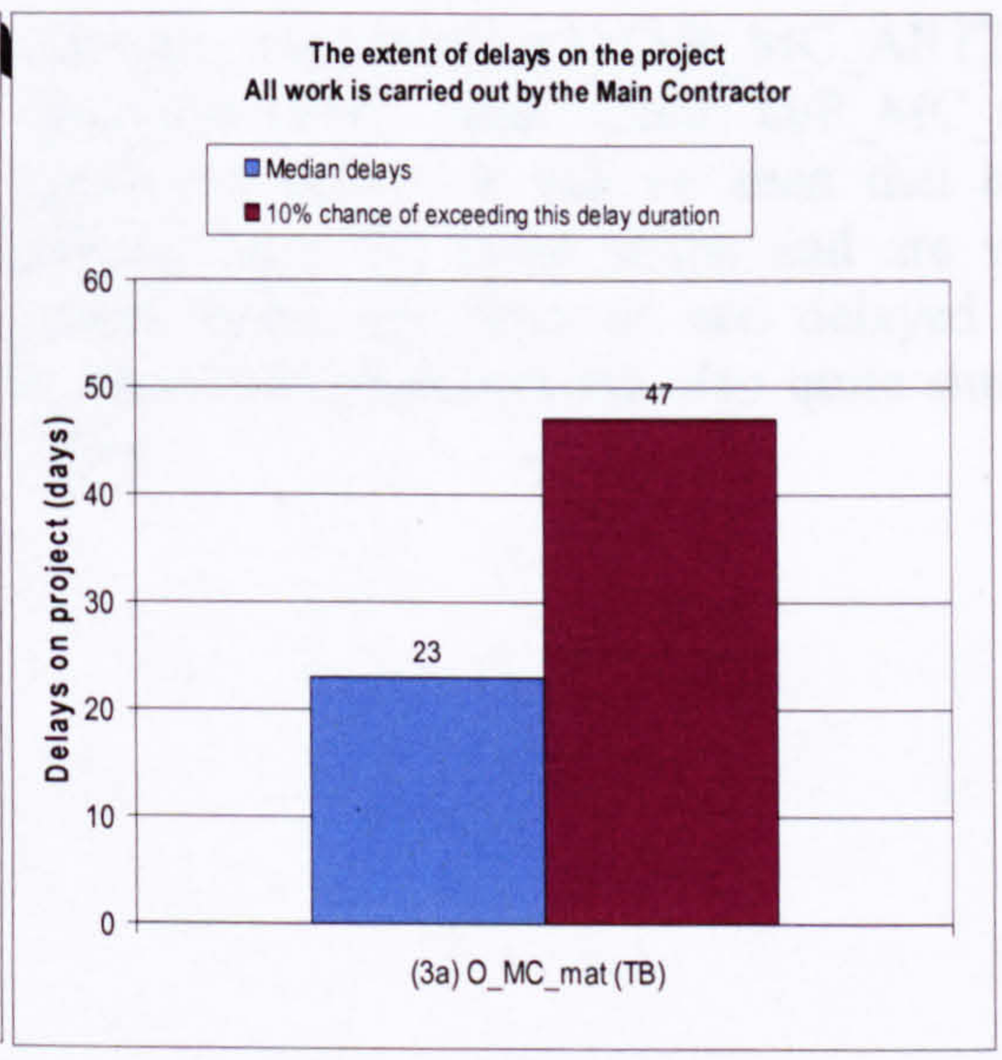
chance of being exceeded is also included. As the extent of the impact of the supply chain delays on the project is the main concern, the median and '10% chance' project durations are converted into project delays by subtracting them from 300 (i.e. project duration without delays), as shown in figure 6-8c below. These measures of delays on the project due to problems along the supply chain can be used to indicate how much supply chain delays may impact on project performance. By comparing these measures from different models, the particular supply chain delay that has the biggest impact on the project can be identified.



a. Frequency distribution of project durations



b. Frequencies with which the project finishes on time or are delayed



c. Extent of delays on the project

Figure 6-8 Understanding the graph of frequency distribution of the results of simulations

6.3 Comparing the optimistic and the pessimistic versions

In the previous chapter, it was mentioned that there are models that have optimistic and pessimistic versions, as shown in table 6-3 below.

Table 6-3 Optimistic and pessimistic models

Optimistic models	Pessimistic models
(1a) O_MC_All (TB)	(1c) P_MC_All (TB)
(1b) O_MC_All (NTB)	(1d) P_MC_All (NTB)
(3a) O_MC_mat (TB)	(3c) P_MC_mat (TB)
(3b) O_MC_mat (NTB)	(3d) P_MC_mat (NTB)
(12a) O_SS_work_sub (TB)	(12c) P_SS_work_sub (TB)
(12b) O_SS_work_sub (NTB)	(12d) P_SS_work_sub (NTB)
(13a) O_SS_work_sup (TB)	(13c) P_SS_work_sup (TB)
(13b) O_SS_work_sup (NTB)	(13d) P_SS_work_sup (NTB)
(14a) O_SS_work_M&E (TB)	(14c) P_SS_work_M&E (TB)
(14b) O_SS_work_M&E (NTB)	(14d) P_SS_work_M&E (NTB)
(15a) O_SS_work_fin (TB)	(15c) P_SS_work_fin (TB)
(15b) O_SS_work_fin (NTB)	(15d) P_SS_work_fin (NTB)

Note: Models begin with "O" are optimistic and models begin with "P" are pessimistic. "TB" = with Time Buffer, "NTB" = No Time Buffer.

The optimistic version represents a best case scenario in which delays on a project occur simultaneously. The pessimistic version represents the worst case scenario when these delays occur consecutively. In these models, delays in optimistic versions are arranged in parallel, while the delays in the pessimistic models are positioned in series, as long as the logic allows this to happen (refer back to chapter 5 for more details).

For the first trial, the histograms of both versions of models (1a/c) O/P_MC_All (TB), (1b/d) O/P_MC_All (NTB), (3a/c) O/P_MC_mat (TB) and (3b/d) O/P_MC_mat (NTB) were compared as shown in figure 6-9 below. It can be seen that both optimistic and pessimistic versions effectively have the same shape and are very close. The frequencies with which projects finish on time or are delayed are effectively the same (figure 6-10a), while their median delays are also quite similar with only 1 to 4 days difference (figure 6-10b).

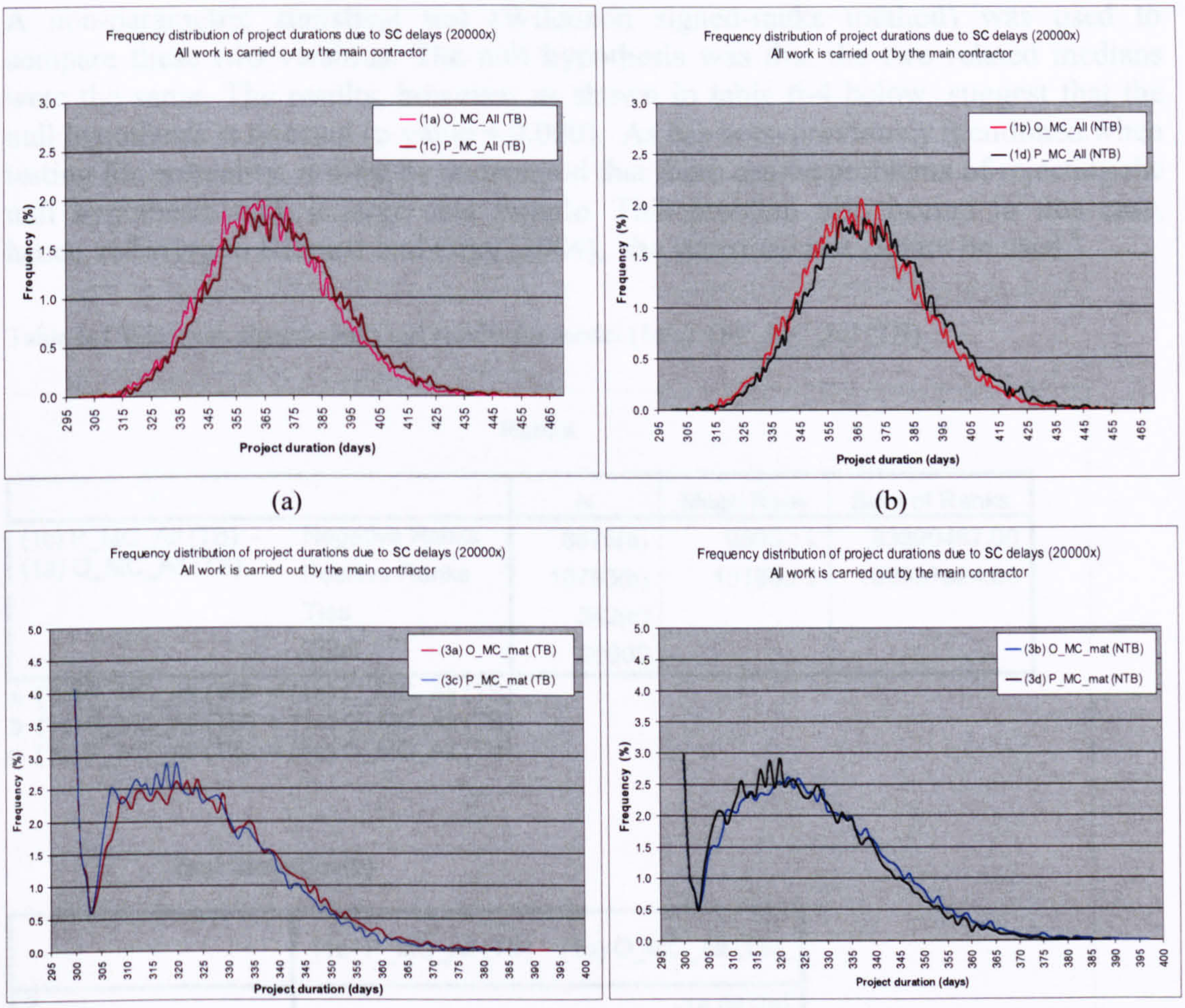


Figure 6-9 Frequency distributions of project durations of models (1) O/P_MC_All (TB/NTB) and (3) O/P_MC_mat (TB/NTB)

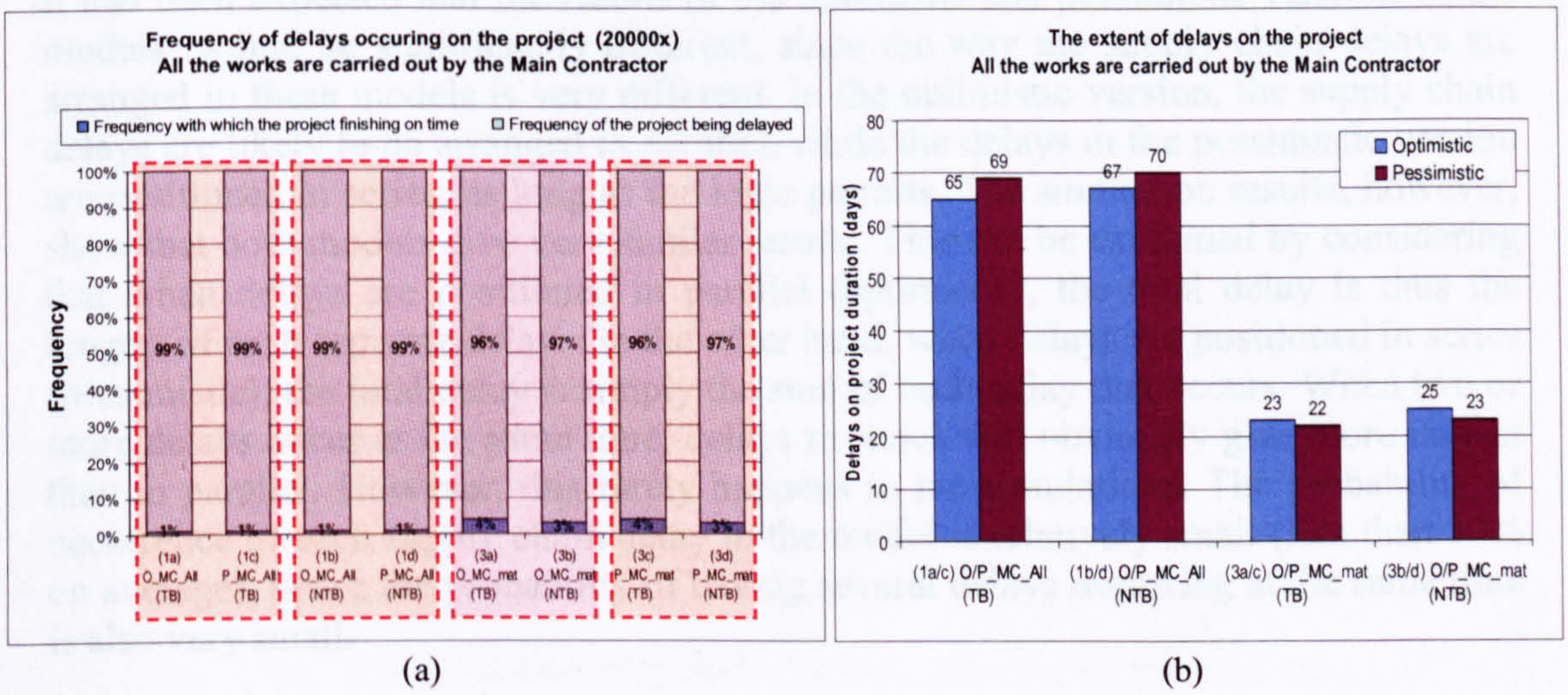


Figure 6-10 Comparing the frequencies and extent of delays of the project (optimistic vs pessimistic)

A non-parametric statistical test (Wilcoxon signed-ranks method) was used to compare these two versions. The null hypothesis was that the two related medians were the same. The results, however, as shown in table 6-4 below, suggest that the null hypothesis is rejected (p-value = 0.000). As has been previously mentioned when testing for normality, it must be understood that there can be problems of rejecting the null hypothesis with a large size sample. This problem also occurs in this case, hence, referring to Kinnear and Gray (2004), the statistical test cannot be used.[4]

Table 6-4 Wilcoxon signed-ranks test results for model (1a/c) O/P_MC_All (TB)

Ranks

		N	Mean Rank	Sum of Ranks
(1c) P_MC_All (TB) - (1a) O_MC_All (TB)	Negative Ranks	8875(a)	9396.11	83390487.00
	Positive Ranks	10783(b)	10186.20	109837824.00
	Ties	342(c)		
	Total	20000		

a (1c) P_MC_All (TB) < (1a) O_MC_All (TB)
b (1c) P_MC_All (TB) > (1a) O_MC_All (TB)
c (1c) P_MC_All (TB) = (1a) O_MC_All (TB)

Test Statistics(b)

	(1c) P_MC_All (TB) - (1a) O_MC_All (TB)
Z	-16.621(a)
Asymp. Sig. (2-tailed)	.000

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

It had been expected that the results of the optimistic and pessimistic versions of the models would be significantly different, since the way the supply chain delays are arranged in these models is very different. In the optimistic version, the supply chain delays are likely to be arranged in parallel, while the delays in the pessimistic version are positioned in series, as long as the logic permits. The simulation results, however, show that both models give very similar results. This can be explained by considering that when delays are positioned in parallel (optimistic), the total delay is thus the longest of each separate delay. On the other hand, when delays are positioned in series (pessimistic), the total delay is simply the sum of each delay that occurs. When two or more delays occur at the same time, delays in series will obviously give more impact than in parallel. However, this rarely happens in the simulations. The probability of occurrence of each supply chain delay in the model is relatively small (less than 30% on average), hence the probability of having several delays occurring at the same time is also very small.

---

[4] A small test comparing optimistic and pessimistic versions of model (1a/c) O/P_MC_All (TB) with various data size can be found in appendix C5. It can be seen that the null hypothesis is accepted with data size of 500 or under. When the data size is larger than 500, the null hypothesis is rejected.

In probability theory, the probability of having two or more independent events occurring simultaneously can be calculated by multiplying the probability of each event. This can be expressed as $P(A \cap B \cap C) = P(A).P(B).P(C)$. For example, if the probability of occurrence of delays A, B and C is 10%, 20% and 30%, then the probability of the three delays occurring simultaneously is 10% x 20% x 30% = 0.60%, which is less than 1%! Using the same formula, the probability of other delays occurring simultaneously can be calculated, as shown in table 6-5 below. It can be seen that the probability of two or three delays occurring simultaneously is small.

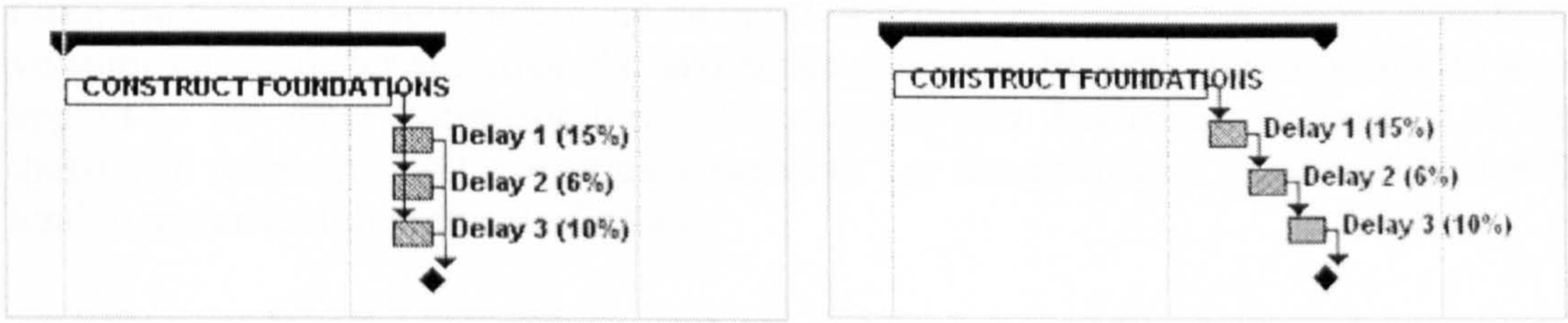
Table 6-5 Probabilities of occurrence of multiple delays

Delays	Possible combinations of occurring delays						
	1	2	3	4	5	6	7
Delay A P(A) =10%	√	-	-	√	√	-	√
Delay P(B) = 20%	-	√	-	√	-	√	√
Delay C P(C) = 30%	-	-	√	-	√	√	√
Probability	**10% = P(A)**	**20% = P(B)**	**30% = P(C)**	**2% = P(A∩B)**	**3% = P(A∩C)**	**6% = P(B∩C)**	**0.6% = P(A∩B∩C)**

√ : delay occurs

- : delay does not occur

A small test below also helps to explain how the relatively small probabilities of occurrence of the delays can be the main cause of the pessimistic and optimistic versions producing similar results. Consider an activity "Construct foundations" that has three delays, with probabilities of occurrence of 15%, 6% and 10% and extent of delays (min, most likely and max) of 1,2,3; 1,1,2 and 2,4,7 days. These delays are arranged in parallel to represent an optimistic version and in series to represent a pessimistic version of the model, as shown in figure 6-11 below.



a. Optimistic version

b. Pessimistic version

Figure 6-11 An example of an activity with optimistic and pessimistic delays

The probability of each delay is then factored up and down as shown in table 6-6 below. These two simple models with various values of probabilities are then run 1000 times. The results are shown in figure 6-12, where medians are used to represent

the distributions. It can be seen that at the initial point (1 times (1x)) or under (1/2x), the median delays are zero[5]. As the probabilities of delays are increased 2, 3 and 4 times, both versions still show the same results. Only after the probabilities of the delays are increased 5 times or more, do the results of the optimistic and pessimistic versions begin to differ. In other words, the bigger the probabilities of the delays, the more likely will the results of both versions be different. These results explain that relatively small probabilities of occurrence of supply chain delays will actually make very little difference between the optimistic and pessimistic versions.

Table 6-6 Various probabilities of occurrence of delays 1, 2 and 3

Delays	Factoring of initial delay probabilities										
	½ x	1x	2x	3x	4x	5x	6x	7x	8x	9x	10x
Delay 1	8%	**15%**	30%	45%	60%	75%	90%	100%	100%	100%	100%
Delay 2	3%	**6%**	12%	18%	24%	30%	36%	42%	48%	54%	60%
Delay 3	5%	**10%**	20%	30%	40%	50%	60%	70%	80%	90%	100%

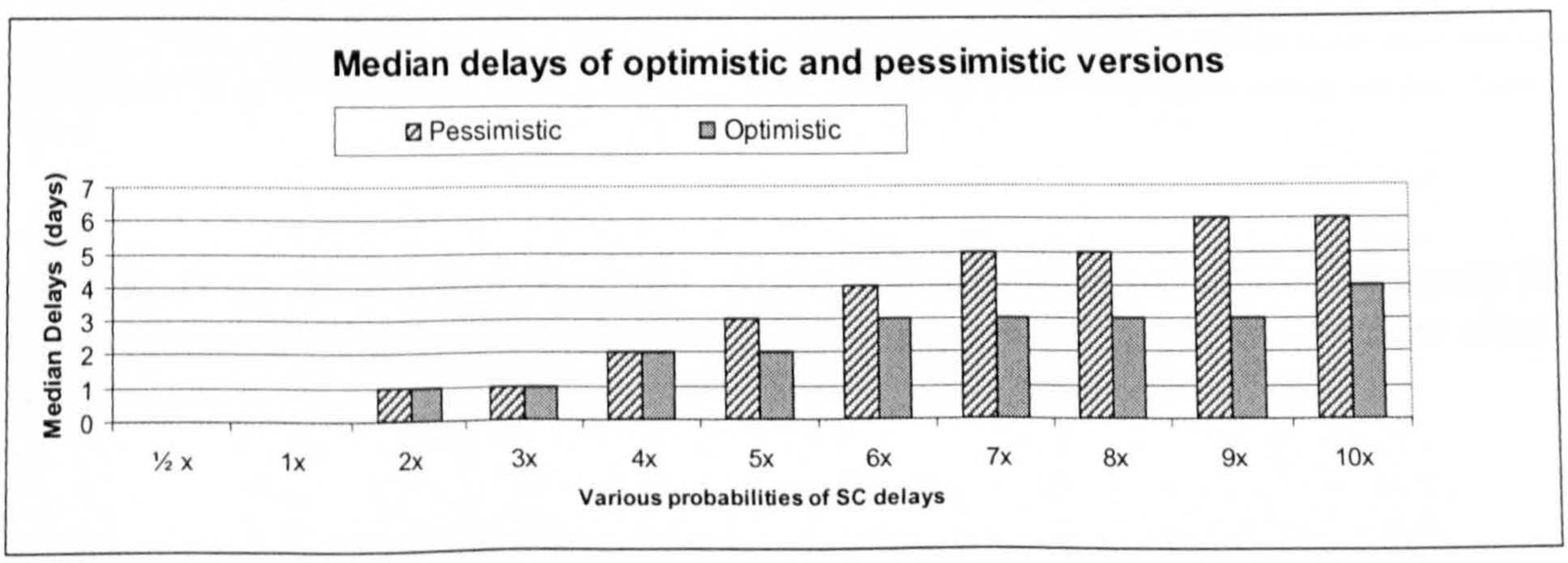


Figure 6-12 Median delays of optimistic and pessimistic versions with various values of probability of occurrence of delays.

It should be noted that the delays incorporated in the simulation models are assumed to be independent. In reality, there are delays which may not be completely independent, meaning that one delay could occur a result of another delay. As this is the first time such a model has been developed, these delays are not considered.

From the previous discussion it can be concluded that the simulation results from both versions do not differ significantly, and hence either can be used. This conclusion also applies to the other optimistic-pessimistic models and discussion in the rest of the thesis will refer only to the best case scenario, i.e. the optimistic version, which will tend to understate the impact of delays.

---

[5] It does not necessarily mean that in this case delays do not occur at all, but with median delays equal to zero, it can be said that effectively delays do not occur.

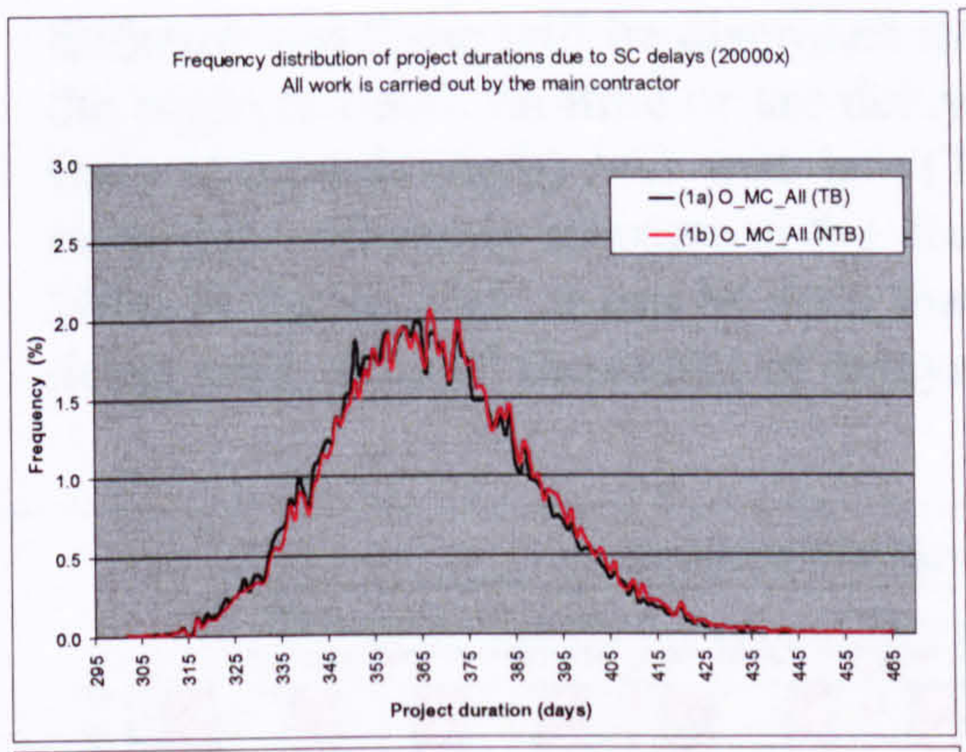
6.4 The provision of time buffers

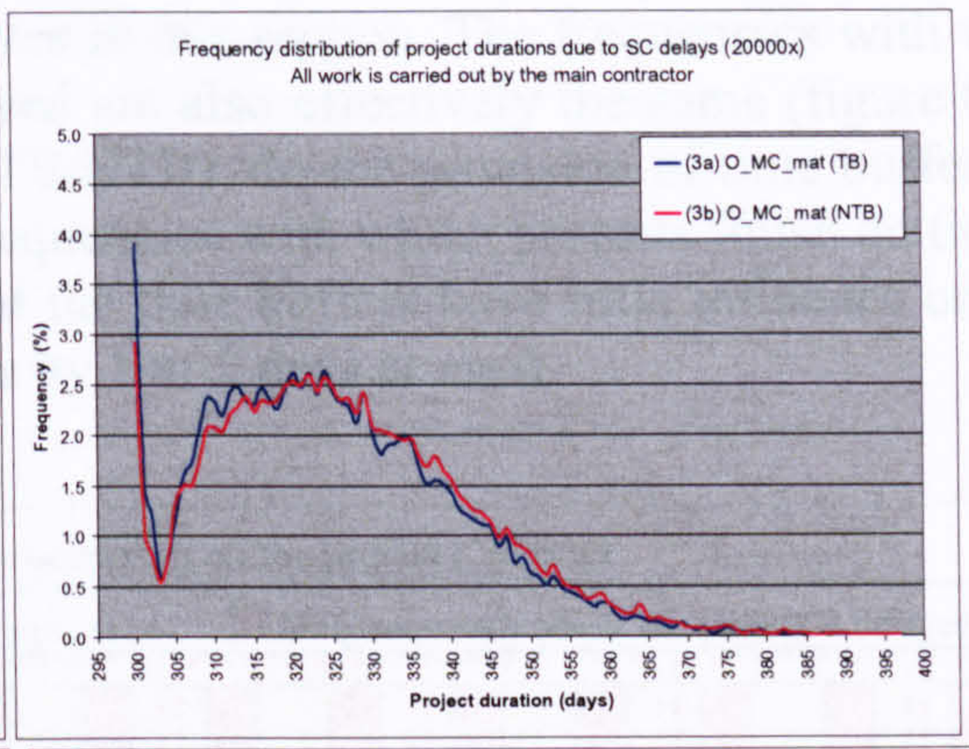
To understand the impact of providing time buffers on a project, some models were allowed to have time buffers to absorb delays. These were then compared with the equivalent models without time buffer. Table 6-7 below shows models with and without time buffers. As it was found that the optimistic or pessimistic versions have similar results, to simplify it was decided to include only the optimistic models in this table.

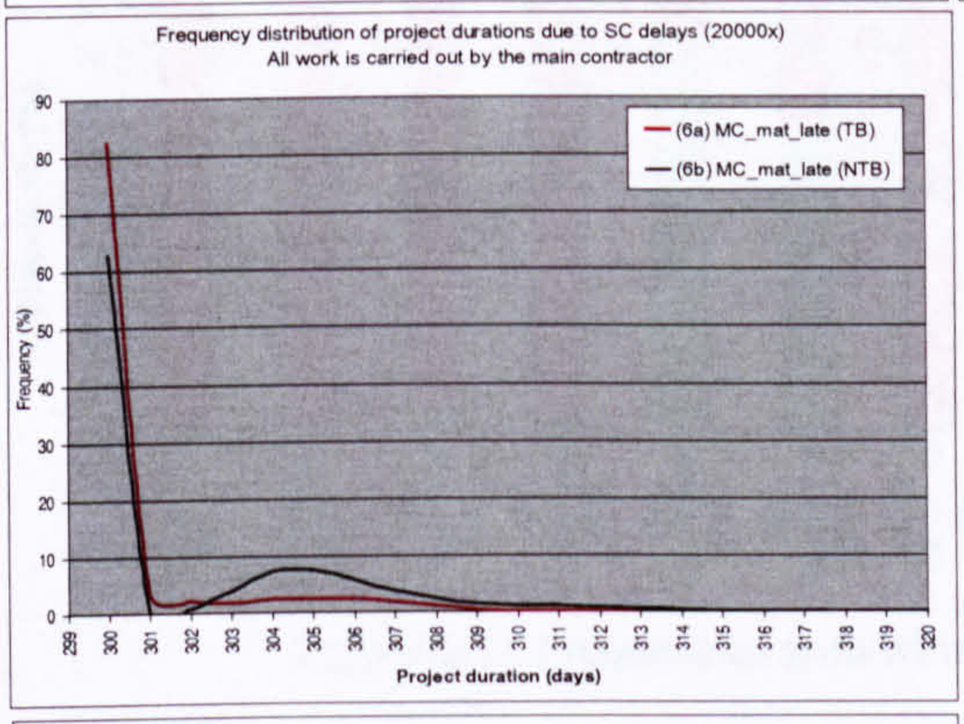
Table 6-7 Models with and without time buffers (TB/NTB)

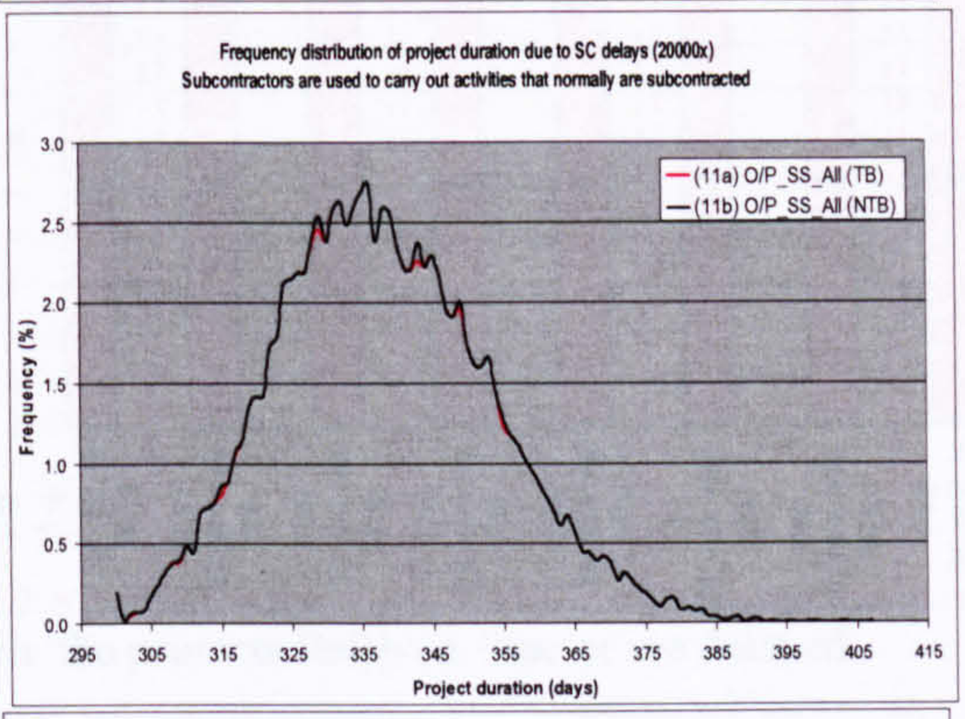
Models with time buffers (TB)	Models without time buffers (NTB)
(1a) O_MC_All (TB)	(1b) O_MC_All (NTB)
(3a) O_MC_mat (TB)	(3b) O_MC_mat (NTB)
(6a) MC_mat_late (TB)	(6b) MC_mat_late (NTB)
(11a) SS_work_all (TB)	(11b) SS_work_all (NTB)
(12a) SS_work_sub (TB)	(12b) SS_work_sub (NTB)
(13a) SS_work_sup (TB)	(13b) SS_work_sup (NTB)
(14a) SS_work_M&E (TB)	(14b) SS_work_M&E (NTB)
(15a) SS_work_fin (TB)	(15b) SS_work_fin (NTB)

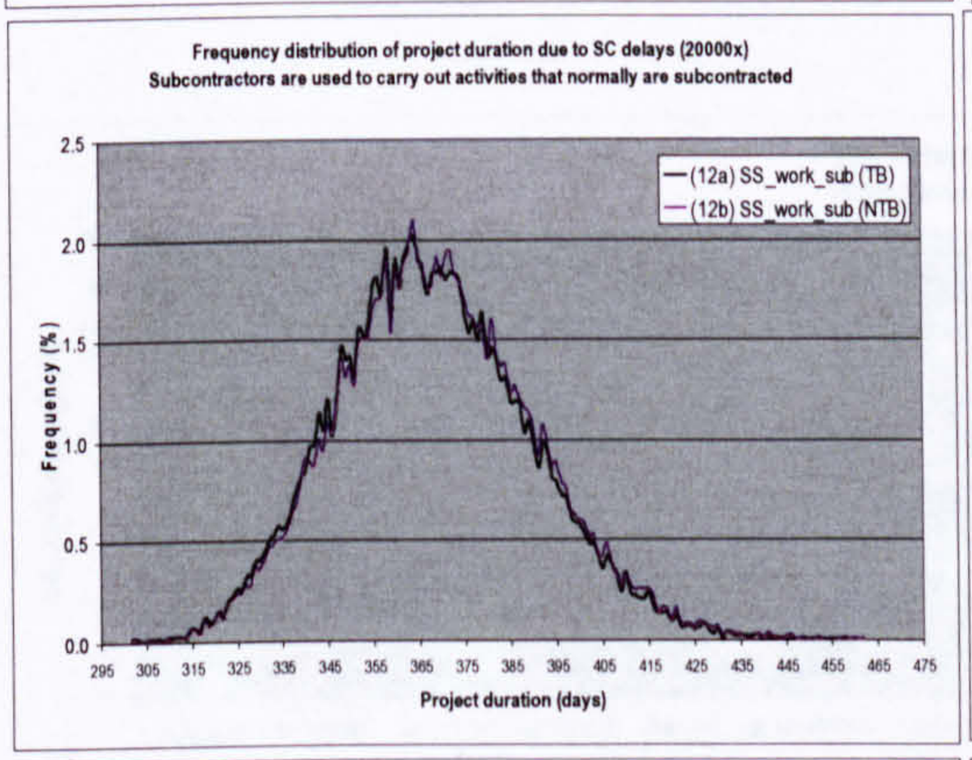
Learning from the previous sections, statistical tests were not used to compare the distributions due to problems related to large sample size. Figure 6-13 below shows the comparison of histograms of models both with and without time buffers.

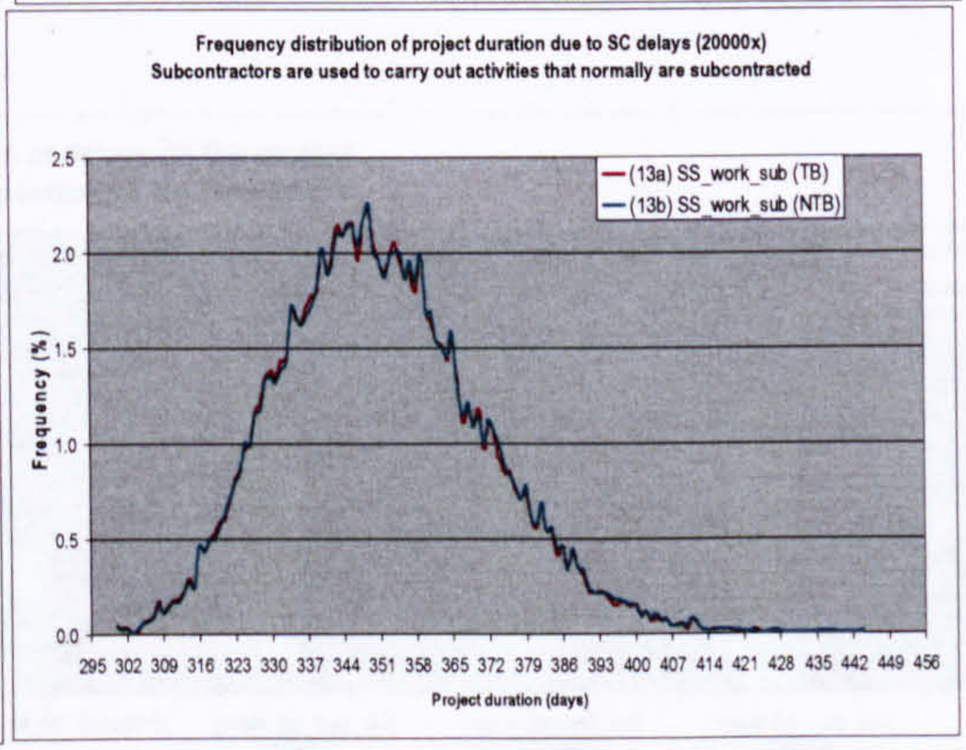


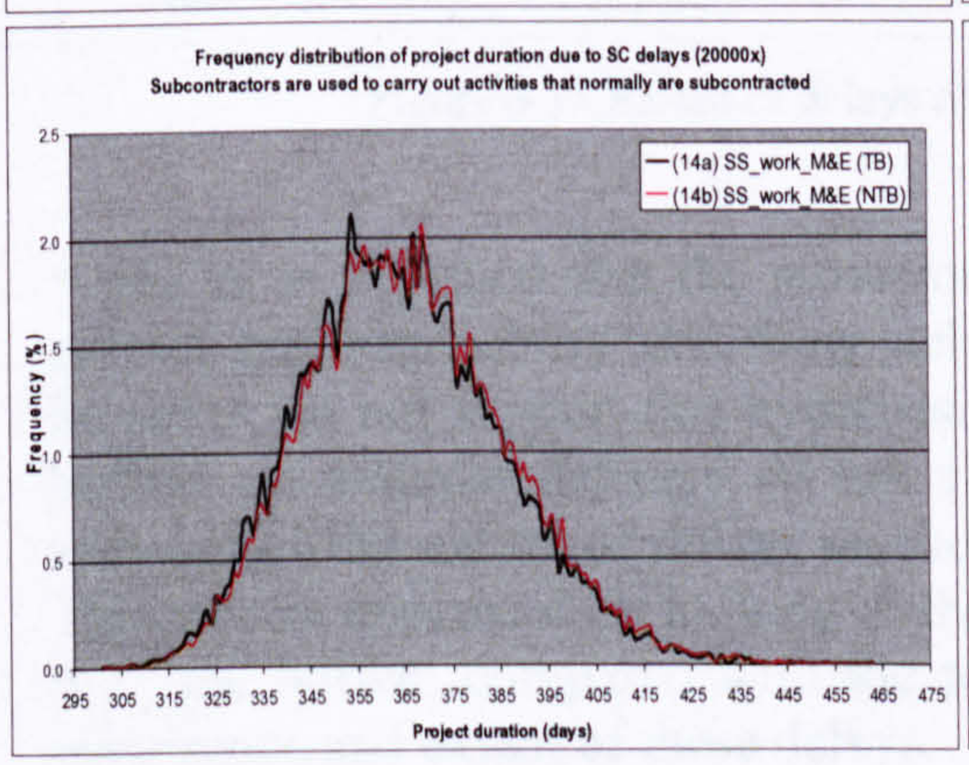












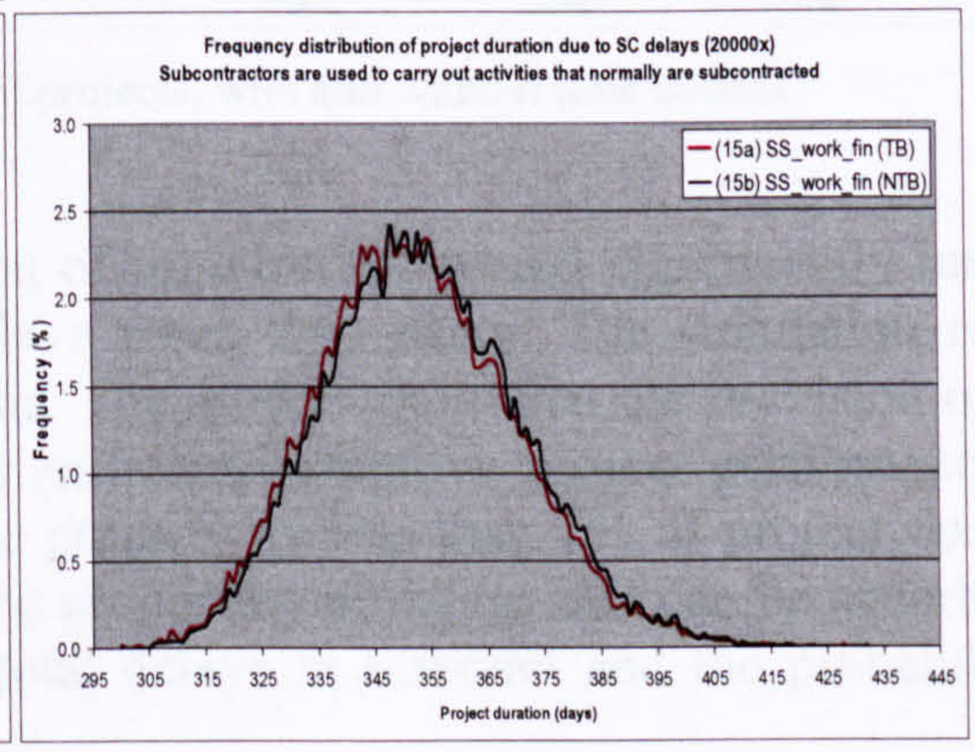


Figure 6-13 Comparing histograms of models with and without time buffers

It can be seen that almost all histograms effectively have the same shape and are very close. Only the histograms of models (6a/b) MC_mat_late (TB/NTB) are noticeably

different and these will be discussed later in this section. The frequencies with which the projects finish on time or are delayed are also effectively the same (figure 6-14). Only in models (6a/b) MC_mat_late (TB/NTB), do the provision of time buffers can make any noticeably increase in the frequencies with which projects finish on time by 20%. In figure 6-15, it can be seen that the time buffers have little influence on total delay, only reduced the extent of delays by 1 or 2 days at most.

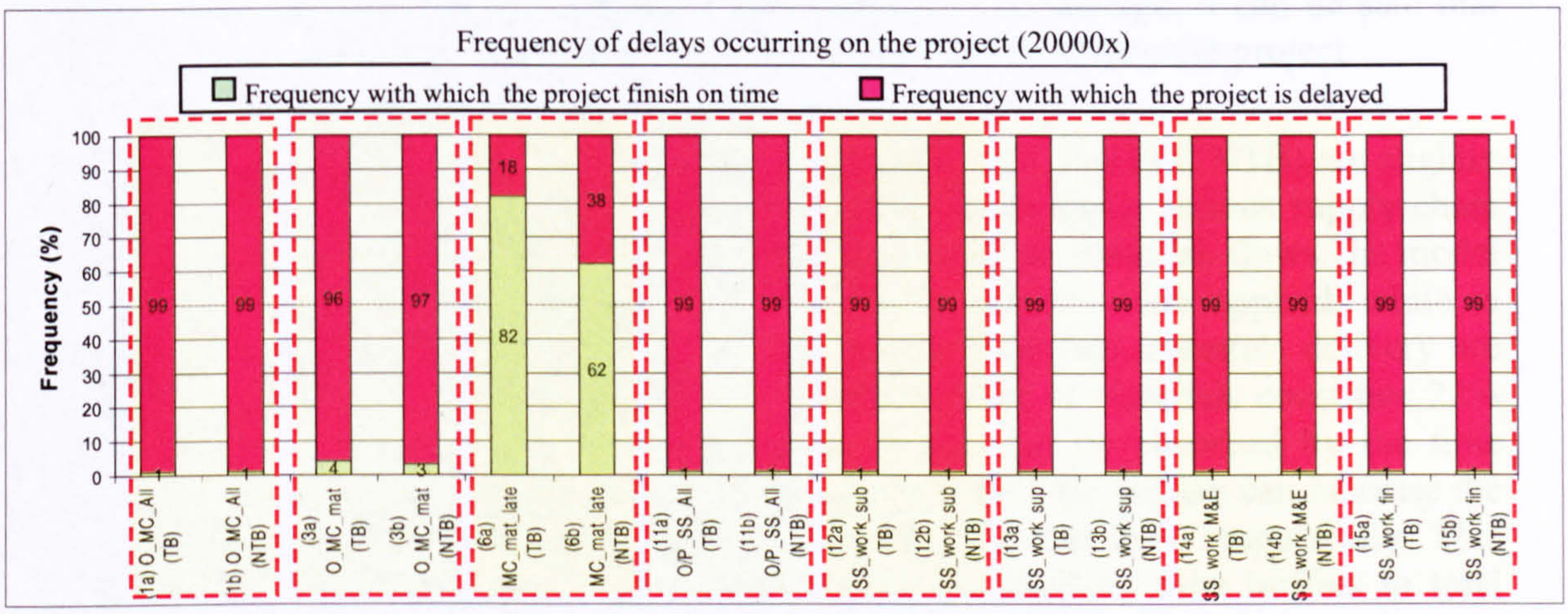


Figure 6-14 Frequencies with which the projects finish on time or are delayed

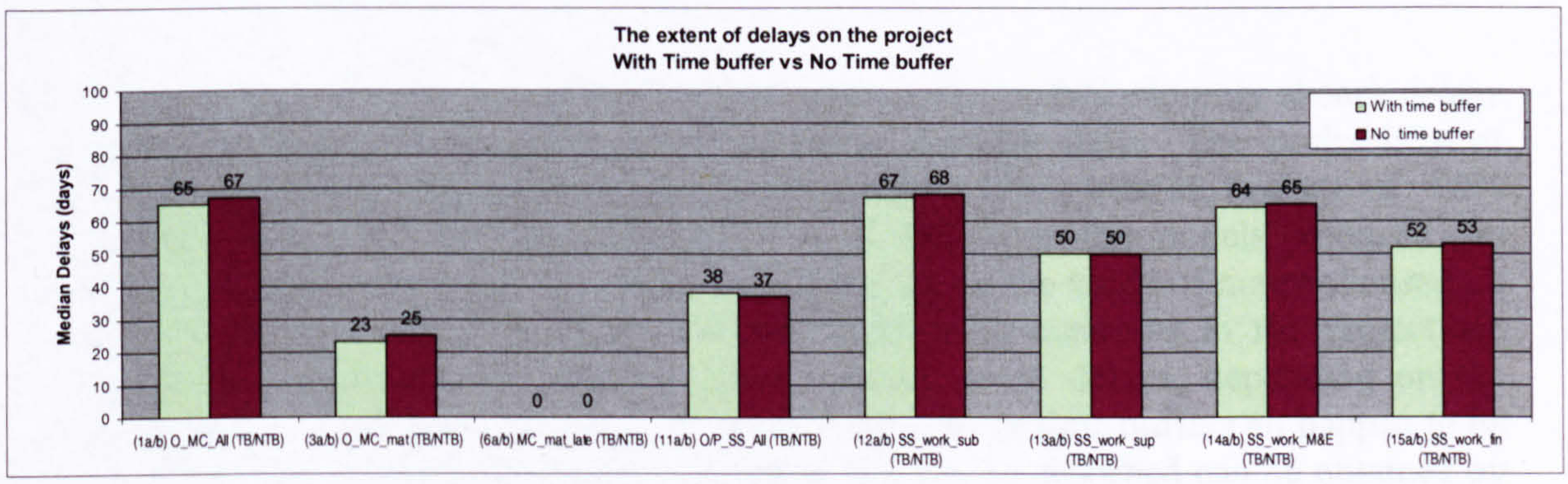


Figure 6-15 Extent of delays of projects, with and without time buffers

It had been expected that the provision of time buffers would significantly improve project performance by absorbing delays when they occur. The simulation results, however, do not support this hypothesis. The models show that the provision of time buffers on material delivery do not significantly improve project performance and only affect the extent of delays on the projects by less than 1% of project duration. This can be explained by looking at the proportion of delays that can be absorbed by the time buffers compared with the total delays in a model and the probability of occurrence and extent of these delays.

There are only at most 8 out of 33 activities in the models that can be delayed by late deliveries of materials. Some models, where activities are subcontracted, have less than 8 (figure 6-16 and table 6-8 row 3). This means that for each model, the time buffers can only absorb delays from late deliveries of materials on these 8 or less activities. As an activity alone can have more than 5 different delays, the delays from

late material deliveries that can be absorbed by the time buffers can thus only be a fraction of the total delays. It can be seen in table 6-8 row 4 below that, apart from models (3a/b) O_MC_mat (TB/NTB) and (6a/b) MC_mat_late (TB/NTB), the delays that can be absorbed by time buffers are only 11% (or less) of the total delays. These results help to explain why with only 11% (or less) delays in a model that can be absorbed by the time buffers, there are no significant differences between the models with and those without time buffers in terms of the frequencies of projects to finish on time during the simulation. With this relatively small percentage, it can be said that the impact of time buffers is hidden by other delays that dominate the project.

Models (3a/b) O_MC_mat (TB/NTB) and (6a/b) MC_mat_late (TB/NTB) are slightly different from the others. Unlike the other models which apply various supply chain delays, these two only have delays which are related to material flows. In model (3a/b) O_MC_mat (TB/NTB), all delays related to materials are applied, while in model (6a/b) MC_mat_late (TB/NTB) only delays from late materials delivery are applied. In both models, these delays due to late delivery of materials constitute 22% and 100% of the total delays in the models, which can be absorbed by the time buffers. The results of these two models suggest that the time buffers can increase the frequencies with which projects finish on time by 1% and 20% respectively. This shows that the proportion of delays that can be absorbed by time buffers to total delays, is an important factor to making time buffers work effectively on a project. In other words, when the delays that include time buffers are a small fraction of the total delays, the impact of time buffers on the project will not be significant.

As previously mentioned, the time buffers used in the models can only absorb delays from materials delivered later than scheduled delivery dates. The probability of occurrence of this type of delay ranges from 7% to 17%, with an average of 10% (refer to table 5-2). A single time buffer on an activity in the models produced can absorb between 4 and 11 days of delay, depending on the kinds of materials used on that particular activity. When all the time buffers on activities in the project are considered together, they may be able to absorb more delays, depending on the particular model concerned. Since the activities that have time buffers all happen to be on the critical path, the total extent of delays that can be absorbed can be obtained by summing up all the time buffers. Table 6-8 row 5 below, shows that the time buffers can potentially absorb delays up to 49 days. This can happen if all the 8 delays of late deliveries of materials occur simultaneously in one simulation, however, this is very unlikely to happen. As the model assumes delays to be independent, the probability of these 8 delays all occurring at the same time in one simulation is extremely very small (0.00000064512%), and is obtained by multiplying their probabilities of occurrence (see table 6-8 row 6). This shows that although the time buffers can potentially absorb a substantial amount of delays in a project and increase the likelihood that the project will finish on time, because of the to small probability that all these delays will occur simultaneously, the overall impact of providing time buffers is not significant.

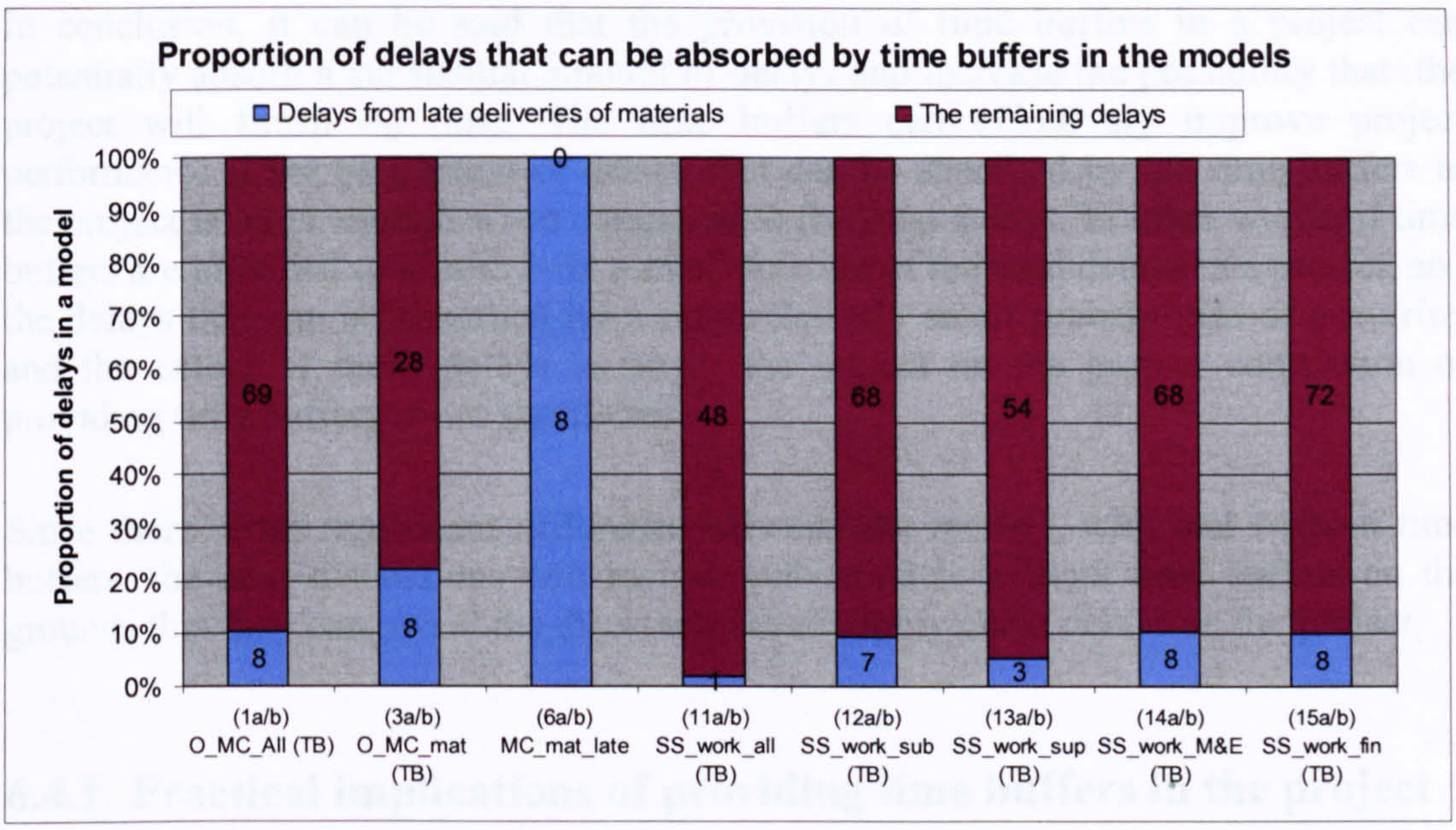


Figure 6-16 Proportion of delays that can be absorbed by the time buffer
(Note: Figures inside the bars are number of delays of each category)

Table 6-8 Activities, delays and results of models with and without time buffers

		(1a/b) O_MC_All (TB/NTB)	(3a/b) O_MC_mat (TB/NTB)	(6a/b) MC_mat_late (TB/NTB)	(11a/b) SS_work_all (TB/NTB)	(12a/b) SS_work_sub (TB/NTB)	(13a/b) SS_work_sup (TB/NTB)	(14a/b) SS_work_M&E (TB/NTB)	(15a/b) SS_work_fin (TB/NTB)
1	Number of activities in the model	33	33	33	33	33	33	33	33
2	Number of total delays in the model	77	36	8	49	75	57	76	80
3	Number of delays from late deliveries of materials that can be absorbed by time buffers	8	8	8	1	7	3	8	8
4	Number of delays from late deliveries of materials in comparisons with the total delays (%)	10%	22%	100%	2%	9%	5%	11%	10%
5	Total extent of delays that can be absorbed by the time buffers in the models	49 days	49 days	49 days	5 days	43 days	22 days	49 days	49 days
6	Probability of all delays in row 3 occurring in one iteration	0.000%	0.000%	0.000%	10%	0.000%	0.001%	0.000%	0.000%
	Results (TB vs NTB)								
7	Frequency with which the projects finish on time	0%	+1%	+20%	0%	0%	0%	0%	0%
8	Extent of delays	-2 days	-2 days	0 day	-1 day	-1 day	0 day	-1 day	-1 day

In conclusion, it can be said that the provision of time buffers in a project can potentially absorb a substantial amount of delays and increase the possibility that the project will finish on time. The time buffers can effectively improve project performance if the proportion of delays that can be absorbed by the time buffers in the project is large enough when compared to the total delays. In other words, if time buffers are provided to absorb only a small fraction of the total delays in a project, and the delays that can be absorbed have only relatively small probabilities of occurring and the extent of these delays is small, the impact on the project completion of providing time buffers is not significant.

Since there is no significant difference between the models, with and without time buffers, the next discussions will include only models without time buffers on the grounds that they can reveal the direct impact of supply chain delays on the project.

6.4.1 Practical implications of providing time buffers in the project

There are some implications from the previous discussion. In practice, providing time buffers for material deliveries means that the materials are expected to arrive on site early, before the activity that uses them starts. The main idea is that if there is an unexpected delay to the delivery of these materials, the activity may still be able to start on time. However, to get the most benefit from providing time buffers, there are several factors to consider, such as: which activities should have time buffers, the space available on site and the main contractor's cash flow.

In a typical school or similar building project, there are many activities that use various types of materials. To get the most benefit from providing time buffers, the main contractor should provide time buffers for activities whose material deliveries are very likely to be delayed, and where the extent of this delay is likely to be high. The more likely the delay to the material delivery, the longer the time buffers that can be provided, as long as the space on site and the main contractor's cash flow allow.

Having materials delivered on site early means that some space is needed to store them until the activity that uses them starts. For projects which have enough space to keep materials on site, the provision of time buffers for material deliveries can be good practice as it can help to reduce the unexpected knock-on problems due to late deliveries of materials. On the other hand, for projects with confined space, the provision of these time buffers may not be very useful. Although it may absorb delays associated with late delivery of materials, with only limited space available, the existence of these materials on site for some time before they are actually needed, could disrupt other activities in the project.

The early delivery of materials can also impact on the main contractor's cash flow. Normally, the main contractor pays the suppliers at a certain period of time after the materials have been delivered to the site and so this early delivery may also require payments to suppliers to be made at an earlier date. Hence, the main contractor's cash flow can be affected. As all main contractors will be concerned about their cash flow, this is obviously a factor to be recognised.

All in all, the provision of time buffers for material delivery can be good practice which can give positive benefits to the project. To get the most out of these benefits, the main contractor should prioritise activities which are very likely to have problems of material delivery with a high extent of delay. However, if space on site is very limited and/or the main contractor is particularly concerned about cash flow, the results of this study would allow the main contractor to argue that as time buffers overall have limited effect, they can be ignored.

6.5 Results of the simulations

This section describes the results of the simulations and explains how they were achieved. For ease of discussion, the description of the results is classified into two categories, i.e. models 1-10, where all work is carried out by the main contractor, and models 11-20, where subcontractors are used in the project. The description is then followed by an explanation of how the various results of the simulations were achieved through a complex simulation process. The implications of the results are also discussed at the end of this section.

6.5.1 Simulations where all the work is carried out by the main contractor

Discounting the pessimistic versions and models with time buffers, there are now 10 models whose activities are carried out solely by the main contractor. They include one model where all supply chain delays are applied at once and the other nine models where these delays are applied one at a time. For ease of discussion, the models are divided into three groups based on how delays are applied in the models. In group 1 is the model where all delays are applied at once. Group 2 consists of models where delays from each flow (information, materials, plant/equipment/temporary work, and labour) are applied one at a time. Group 3 encompasses models which only consider delays in material flow, one at a time. Table 6-9 below, shows the grouping of the models and how supply chain delays are applied in the models.

Table 6-9 Grouping of models where all work is carried out by the main contractor

Group	Models	How delays are applied
Group 1	(1b) O_MC_all (NTB)	All delays are applied at once
Group 2	(2) MC_info	Delays are applied one at a time
	(3b) O_MC_mat (NTB)	
	(4) MC_plant	
	(5) MC_lab	
Group 3	(6b) MC_mat_late (NTB)	Delays in material flow are applied one at a time
	(7) MC_mat_wro	
	(8) MC_mat_dmg	
	(9) MC_mat_ins	
	(10) MC_mat_diff	

The results of these models are shown in figures 6-17 and 6-18 below. Figure 6-17 shows the frequencies with which projects finish on time or are delayed, while figure 6-18 shows the extent of delays (median) and the delay which has a 10% chance of being exceeded.

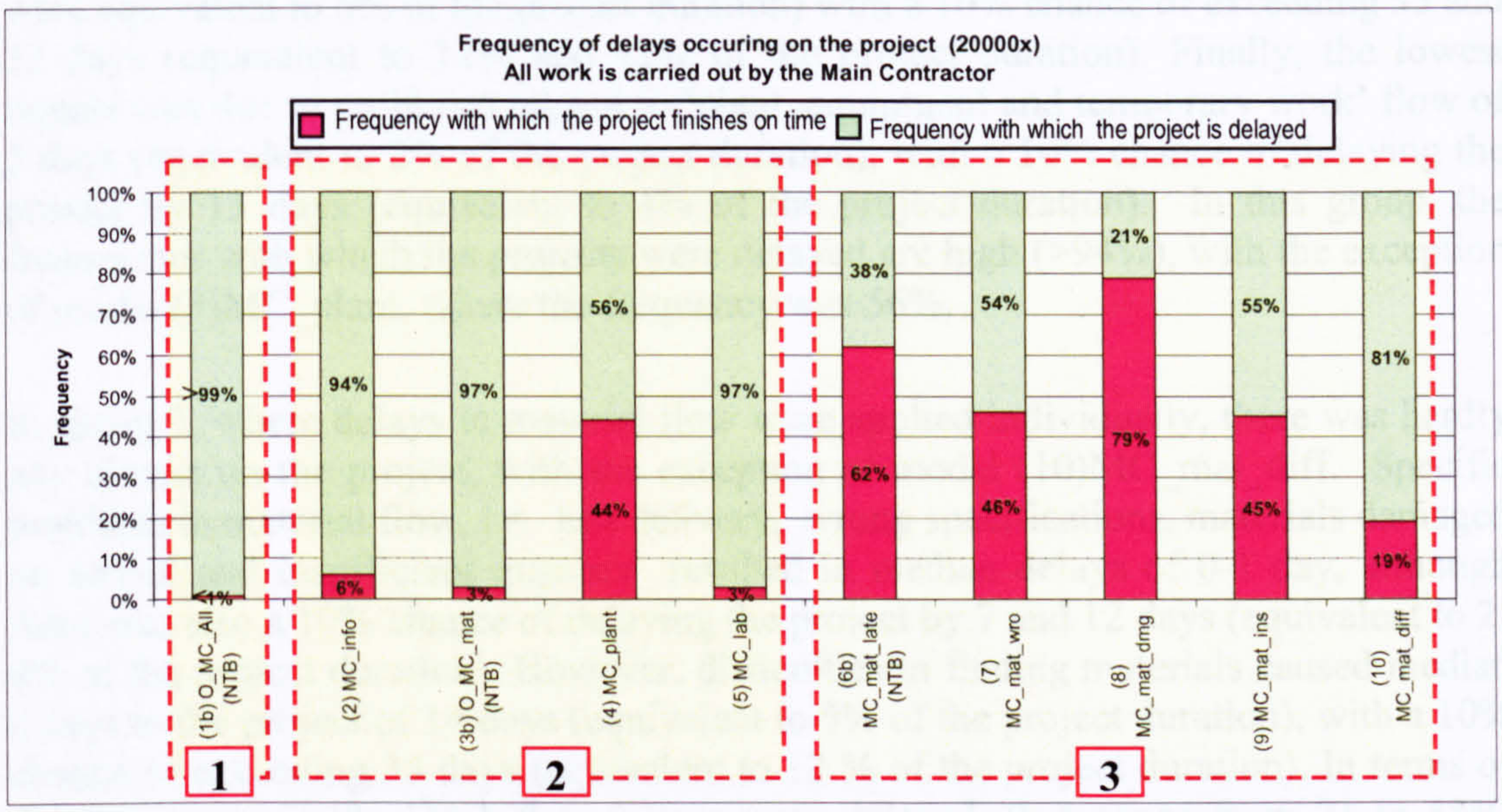


Figure 6-17 Frequencies with which the projects finish on time or are delayed

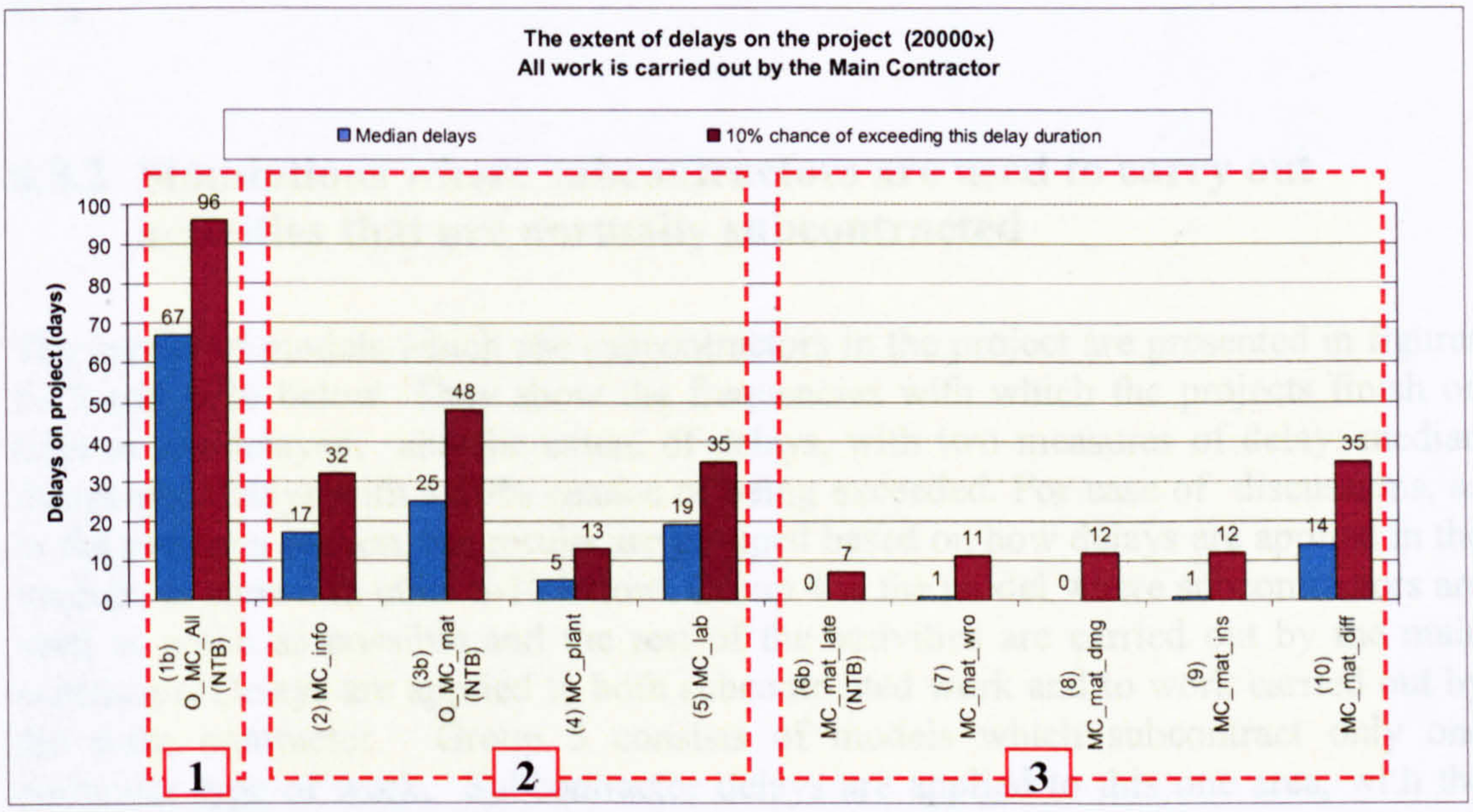


Figure 6-18 The extent of delays on the project

Model (1b)O_MC_All (NTB) in group 1 represents a project where all the work is carried out by the main contractor with all possible supply chain delays related to information flow, material flow, 'plant, equipment and temporary work' flow and labour flow. It can be seen in figure 6-18 that the project's median delay was 67 days (equivalent to 22% of the project duration). There was also a 10% chance of exceeding 96 days (equivalent to 32% of the project duration). In this model, the project had only a small chance (less than 1%) of finishing on time (figure 6-17).

In group 2, the extent of median delays ranges from 5 to 25 days (equivalent to 2 to 8% of the project duration). It can be seen that material flow has the biggest impact on the project with median delays of 25 days and a 10% chance of delaying the project by 48 days (equivalent to 16% of the project duration). Delays due to the labour flow and the information flow were not significantly different, i.e. 19 and 17 days (both were equivalent to 6% of the project duration) with a 10% chance of exceeding 35 and 32 days (equivalent to 12% and 11% of the project duration). Finally, the lowest impact was due to problems related to 'plant, equipment and temporary work' flow of 5 days (equivalent to 2% of the project duration), with a 10% chance of delaying the project by 13 days (equivalent to 4% of the project duration). In this group, the frequencies with which the projects were delayed are high (>94%), with the exception of model (4)MC_plant, where the frequency was 56%.

In group 3, where delays in material flow were applied individually, there was hardly any impact on the project, with the exception of model (10)MC_mat_diff. Specific problems in material flow, i.e. late delivery, wrong specifications, materials damaged on arrival and insufficient quantity resulted in median delays of 0-1 day, although there was also a 10% chance of delaying the project by 7 and 12 days (equivalent to 2-4% of the project duration). However, difficulties in finding materials caused median delays to the project of 14 days (equivalent to 5% of the project duration), with a 10% chance of exceeding 35 days (equivalent to 12 % of the project duration). In terms of the frequencies with which the projects were delayed, they range from 21 to 55%, with an exception in the case of delays due to difficulties in finding materials, of 81%.

6.5.2 Simulations where subcontractors are used to carry out activities that are normally subcontracted

The results of models which use subcontractors in the project are presented in figures 6-19 and 6-20 below. They show the frequencies with which the projects finish on time or are delayed, and the extent of delays, with two measures of delay: median delays and delays with a 10% chance of being exceeded. For ease of discussions, as in the previous section, the results are grouped based on how delays are applied in the models, as shown in table 6-10 below. Group 4 is the model where subcontractors are used as much as possible and the rest of the activities are carried out by the main contractor. Delays are applied to both subcontracted work and to work carried out by the main contractor. Group 5 consists of models which subcontract only one particular type of work. Subcontractor delays are applied to this one area, with the rest of the activities attracting main contractor delays. Group 6 is like group 4 with all activities subcontracted that can be, but here no delays are applied to activities carried out by the main contractor, only all subcontractor delays are applied without any other delays. Group 7 encompasses models where only one type of work is subcontracted and delays are applied, with no other delays. A model in group 1 from the previous section is also included in the figures 6-19 and 6-20, as this model will be used later as a benchmark to compare with other models in this section.

Table 6-10 Grouping of models where subcontractors are used

Group	Models	How delays are applied
Group 4	(11b) O/P_SS_All (NTB)	Subcontractors are used as much as possible. The remaining work is carried out by the main contractor.
Group 5	(12b) SS_work_sub (NTB)	Subcontractors are used for a particular work. The rest is carried out by the main contractor.
	(13b) SS_work_sup (NTB)	
	(14b) SS_work_M&E (NTB)	
	(15b) SS_work_fin (NTB)	
Group 6	(16) SO_All	Only all subcontractor delays are applied
Group 7	(17) SO_work_sub	Only individual subcontractor delays are applied.
	(18) SO_work_sup	
	(19) SO_work_M&E	
	(20) SO_work_fin	

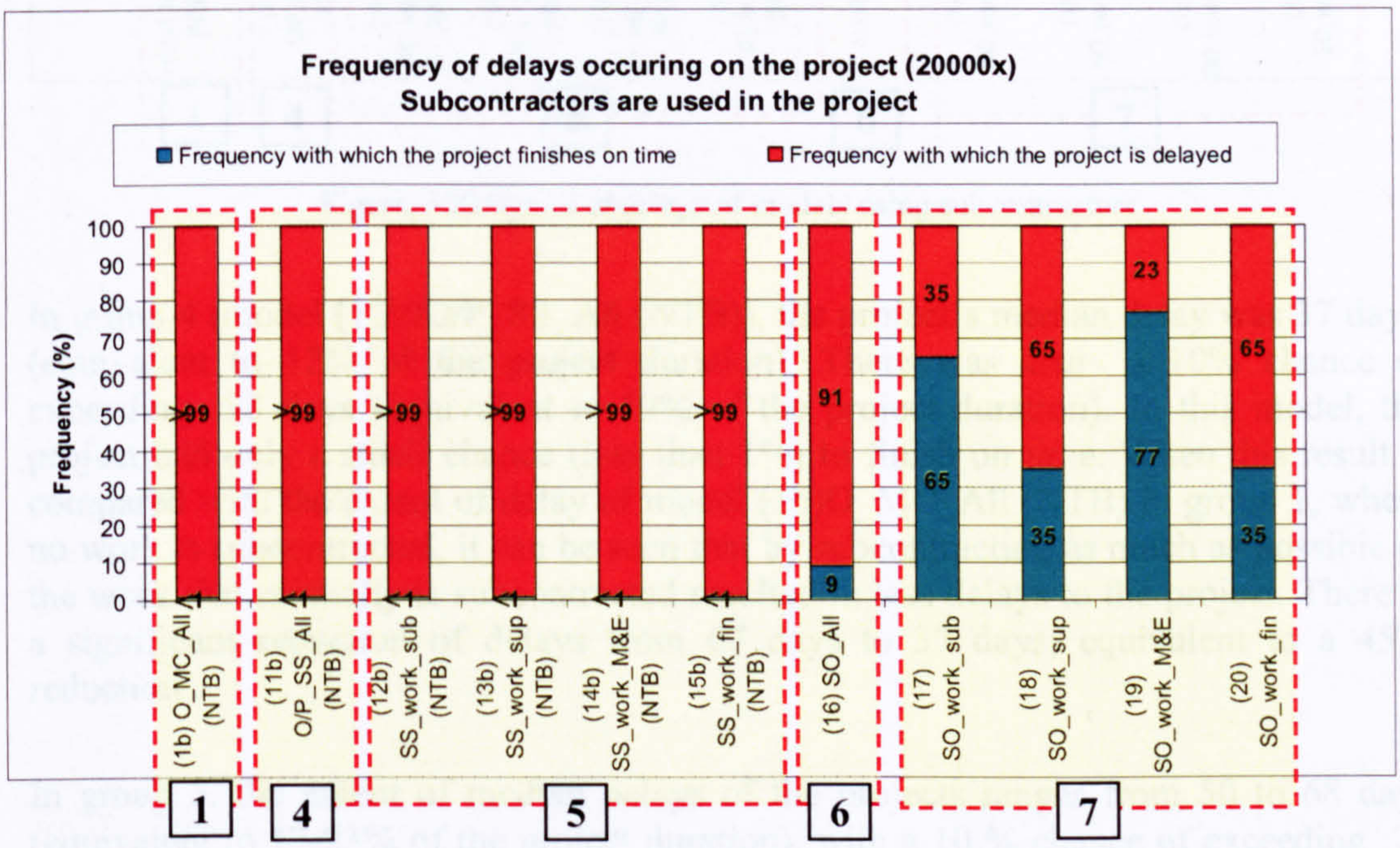


Figure 6-19 Frequencies with which the projects finish on time or are delayed

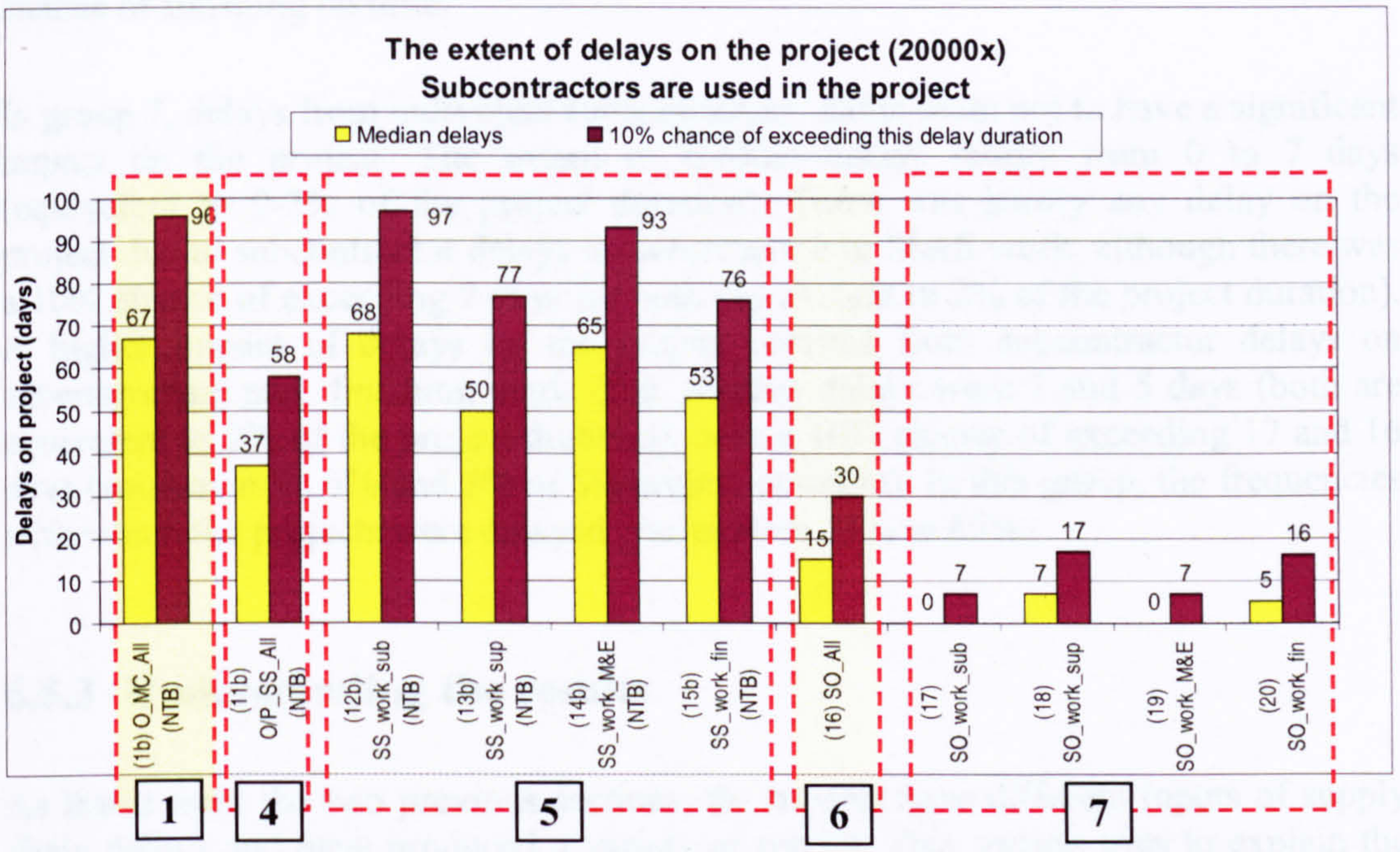


Figure 6-20 Extent of delays of models using subcontractors

In group 4 (model (11b)O/P_SS_All (NTB)), the project's median delay was 37 days, (equivalent to 12% of the project duration). There was also a 10% chance of exceeding 58 days (equivalent to 19% of the project duration). In this model, the project had only a small chance (less than 1%) to finish on time. When this result is compared with the extent of delay of model (1b)O_MC_All (NTB) in group 1, where no work is subcontracted, it can be seen that by subcontracting as much as possible of the work that normally is subcontracted resulted in less delays to the project. There is a significant reduction of delays from 67 days to 37 days; equivalent to a 45% reduction .

In group 5, the extent of median delays of the projects ranges from 50 to 68 days (equivalent to 17-23% of the project duration), with a 10 % chance of exceeding 76 to 97 days (equivalent to 25-32% of the project duration). When these results are compared with the extent of delays in model (1b)O_MC_All (NTB) in group 1, it can be seen that subcontracting substructure work or M&E work did not make a significant difference to the extent of delays. Subcontracting these two, only resulted in 1-2 days difference in delays (equivalent to less than 1% of the project duration). However, there was a substantial reduction of delays when subcontracting superstructure or finishing work: by 17 and 14 days (equivalent to 6% and 5% of the project duration). In terms of the frequencies with which the projects were delayed, the models in this group had only a small chance (less than 1%) of finishing on time.

In groups 6 and 7 are models which include only subcontractor delays. Hence, the results of these groups should reveal the pure impact of subcontractor delays on the project. In group 6 (model (16)SO_All), it can be seen that when all subcontractor delays only were applied, the project's median delay was 15 days (equivalent to 5% of the project duration). There was also a 10% chance of this delay exceeding 30 days

(equivalent to 10% of the project duration). In this model, the project had only a 9% chance of finishing on time.

In group 7, delays from individual subcontractors alone seem not to have a significant impact on the project. The extent of median delays ranges from 0 to 7 days (equivalent to 0-2% of the project duration). There was hardly any delay on the project due to subcontractor delays on substructure or M&E work, although there was a 10% chance of exceeding 7 days for both (equivalent to 2% of the project duration). A higher impact of delays on the project resulted from subcontractor delays on superstructure and finishing work. The median delays were 7 and 5 days (both are equivalent to 2% of the project duration), with a 10% chance of exceeding 17 and 16 days (equivalent to 6% and 5% of the project duration). In this group, the frequencies with which the projects were delayed varies from 23% to 65%.

6.5.3 Understanding the results

As learnt from the two previous sections, the models have different inputs of supply chain delays and have produced a variety of results. This section tries to explain the complex process of the simulations and how the various delays on the project were achieved.

6.5.3.1 P, E, C and median delays

In the original network there are 33 activities, 19 of which are critical. Each activity has a range of types and number of delays which may affect it. The impact of these delays on an activity depends on their probability of occurrence and on the actual extent of the delays. At project level, the total delay on the project will likely be the sum of the delays on the critical path. Although the critical path may change during the simulations, the criticality index of the models, as discussed in section 6.1.2, suggests that most of the critical activities remain critical during most of the simulations. In other words, the critical path of the original network is critical for most of the simulations. Hence, it could be said that at project level, the total delay on the project can be explained using the delays of activities on the original critical path.

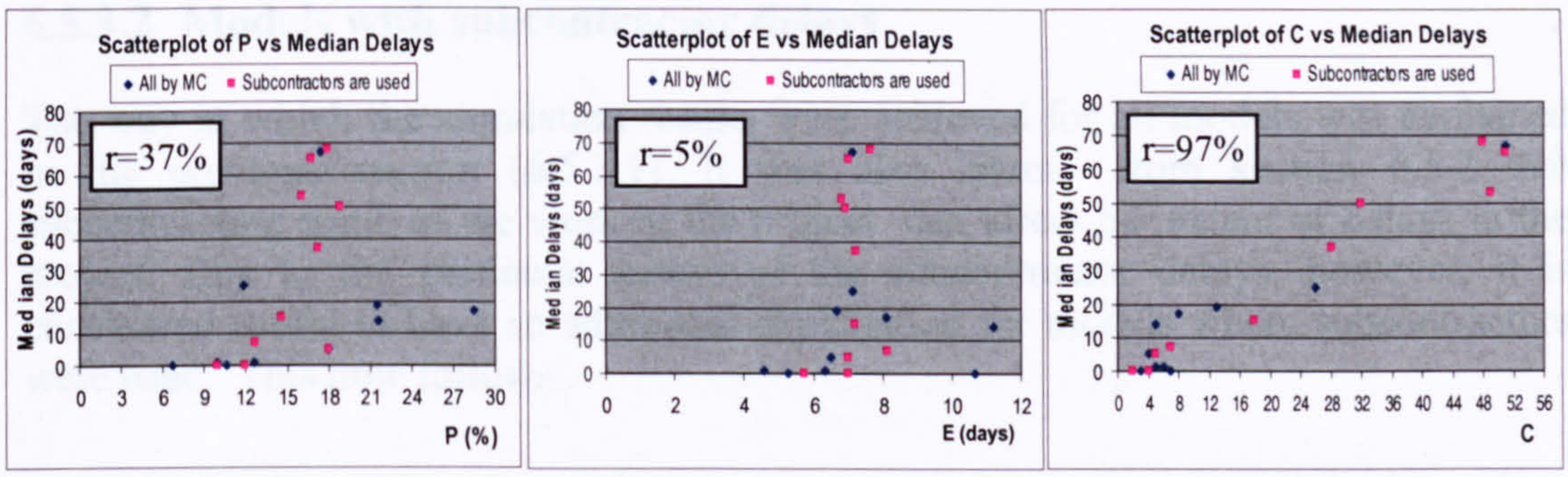
From the description above, it can be seen that there are three main factors that generate the output of the simulations, namely: the probability of delays (P), the extent of delays (E) and the number of delays on the critical path (C). These three factors, which are independent of one another, generate the outputs through a complex process in the network. Theoretically, it can be said that the higher the values of P, E and C, the higher the extent of delays on the project will be. To represent the values of P and E at project level, the average values of P and E (most likely) for delays on the original critical path were used. Table 6-11 below shows the values of P, E, and C for each model, as well as the median delays resulting from the simulations.

Table 6-11 P, E, C and median delays of the project

	(1b) O_MC_All (NTB)	(2) MC_info	(3) O/P_MC_mat	(4) MC_plant	(5) MC_lab	(6) MC_mat_late (TB/NTB)	(7) MC_mat_wro	(8) MC_mat_dmg	(9) MC_mat_ins	(10) MC_mat_diff	(11b) SS_work_all (NTB)	(12) O/P_SS_work_sub (TB/NTB)	(13) O/P_SS_work_sup (TB)	(14) O/P_SS_work_M&E (TB/NTB)	(15) O/P_SS_work_fin (TB/NTB)	(16) SO_All	(17) SO_work_sub	(18) SO_work_sup	(19) SO_work_M&E	(20) SO_work_fin
P (%)	17.5	28.5	11.9	18.0	21.5	6.7	10.0	10.7	12.6	21.6	17.3	18.0	18.8	16.8	16.1	14.6	10.0	12.7	12.0	18.0
E (days)	7.1	8.1	7.2	6.5	6.7	5.3	6.3	10.7	4.6	11.2	7.3	7.7	6.9	7.1	6.9	7.2	5.8	8.1	7.0	7.0
C	51	8	26	4	13	7	6	3	5	5	28	48	32	51	49	18	4	7	2	5
Median Delays	67	17	25	5	19	0	1	0	1	14	37	68	50	65	53	15	0	7	0	5
P*E*C	64	19	22	5	19	2	4	3	3	12	35	66	42	61	54	19	2	7	2	6

It can be seen that each model has different values of P, E and C. The values of P range from 6.7 to 28.5%, the E values range from 4.6 to 11.2 days, and C values range from 2 to 51. For each model, it is the combination of these three factors that will determine the final delays to the project.

To find out how much each of these factors contributes to project delays, their correlations with the median delays can be used as a measure. The scatterplots of P and E against the median delays suggest that they have relatively low correlations with the median delays of 37% and 5% respectively, as shown in figure 6-21 (a) and (b) below. However, C has a very strong positive correlation with the median delays, with r=97% (figure 6-21 (c)). This suggests that, for this typical CPM network, the C factor, i.e. the number of delays on the critical path, is likely to be the main determinant of the various median delays of the project. Models (1b) and (11) can best illustrate this. They both have similar values of P (17.5% and 17.3%) and E (7.1 and 7.3 days), but their C values are quite different, of 51 and 28 units. The results show that their median delays are also very different, i.e. 67 and 37 days respectively.



(a) (b) (c)

Figure 6-21 Scatterplots of P, E dan C against median delays

It was later found that for this typical CPM network, the median delays of the models can actually be estimated using these three values, i.e. by multiplying P, E and C. The results of multiplying these three are very close to the median delays of the simulations (see table 6-11 and figure 6-22). The errors of this approach are not significant, ranging from 0% to 7%, with the exception of model (13) which has an error of 12%.

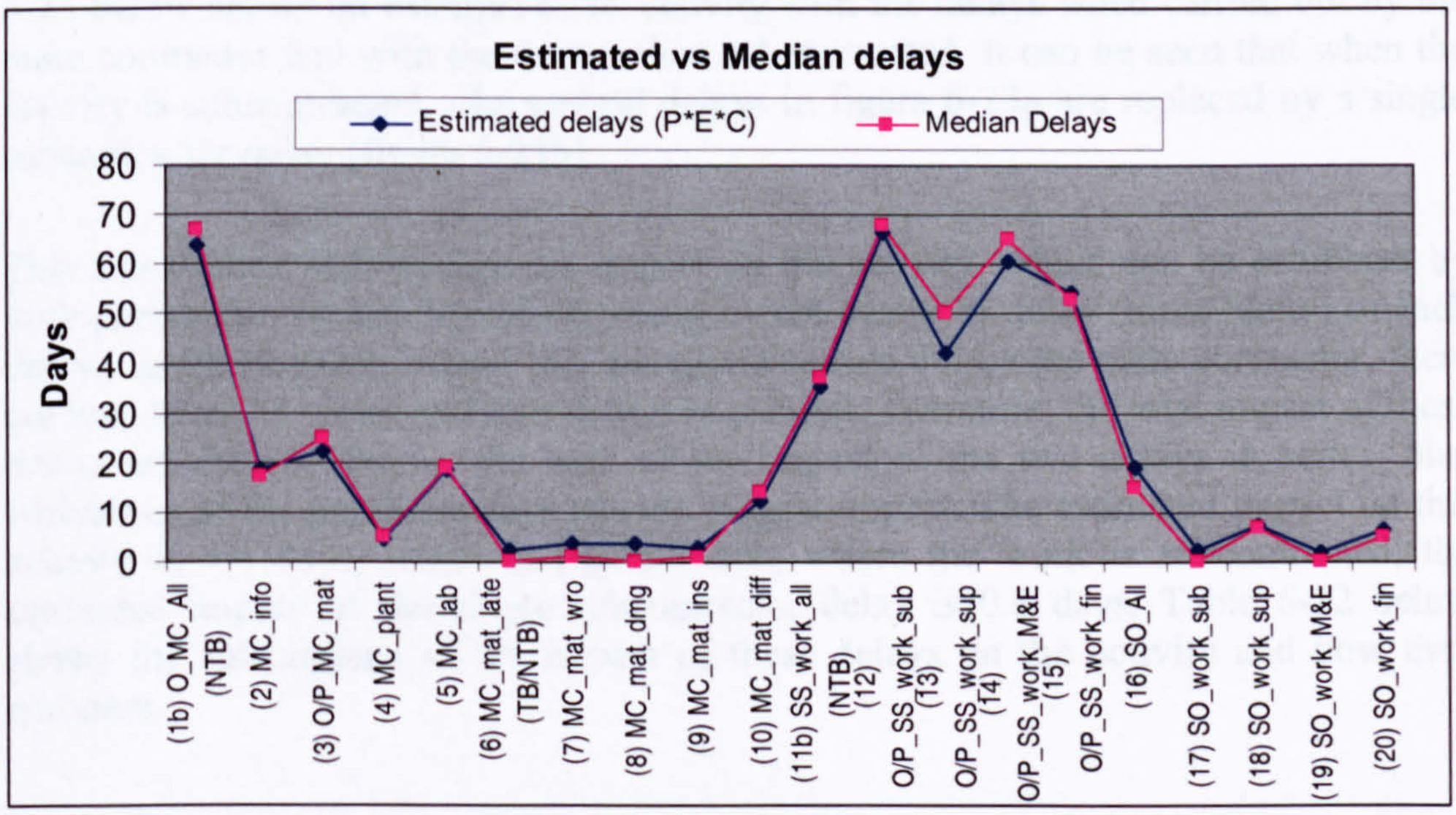


Figure 6-22 Estimated versus median delays of simulations

It can be concluded that for this typical CPM network, where the critical path of the original network remains critical for most of the simulations, the extent of delays can be estimated by multiplying these three factors. Further tests may be needed, however, if this approach is to be used to estimate the median delays for other types of networks, which are more complex and may have more critical paths.

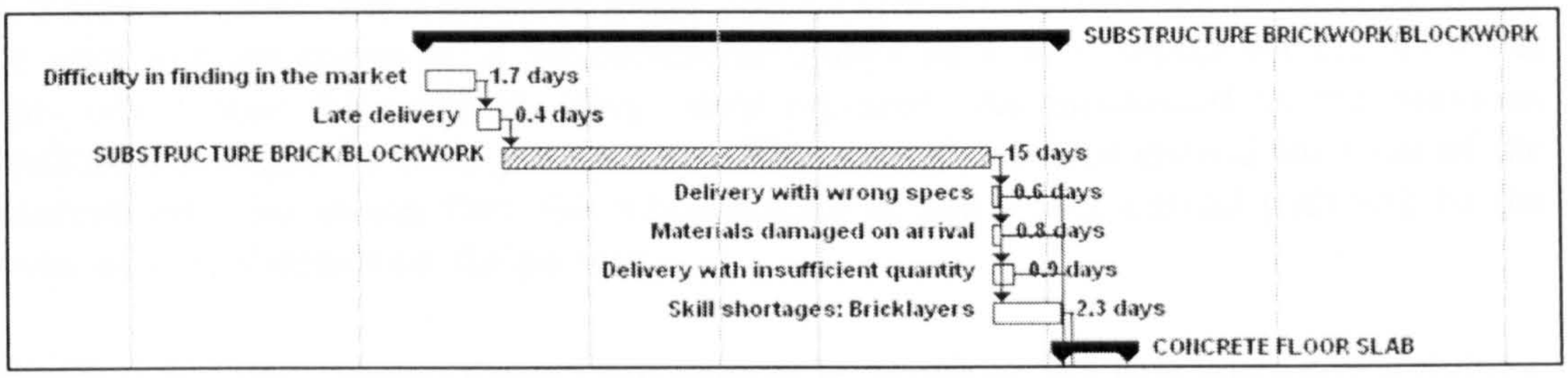
6.5.3.2 Models with subcontractor delays

The way in which the simulation results were achieved for all models was explained in the previous section (6.5.3.1). It was also learnt from section 6.5.2 that subcontracting some of the work in the project can affect the extent of delays in the project. Due to the particular nature of the subcontractor delays, however, it is considered useful to have an additional explanation for models where subcontractors were used. This now follows.

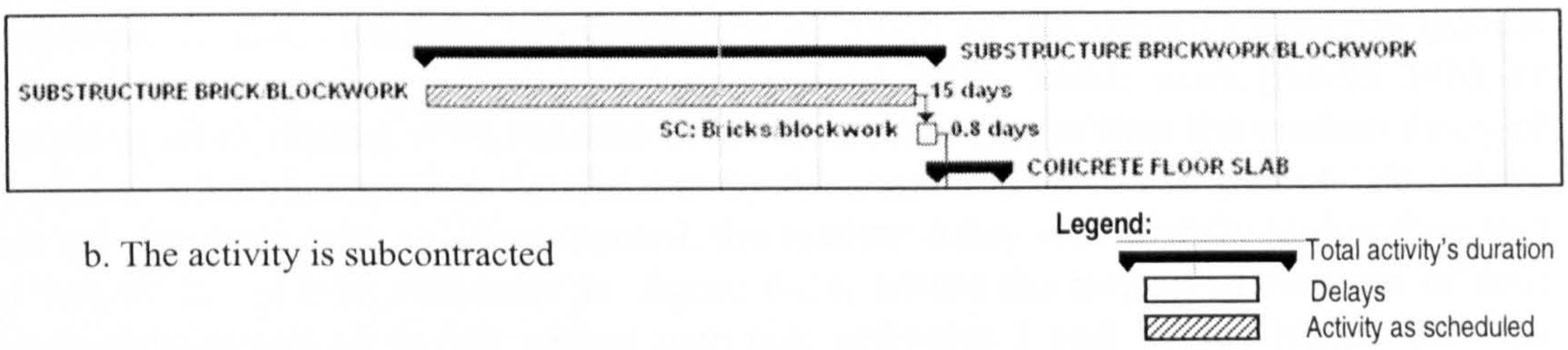
In models (11b) – (20), where subcontractors are used to carry out work in the project, it was assumed that any delays on this subcontracted work are under the subcontractors' control. Hence, in these models, the subcontractor delays are applied to these subcontracted activities and basically, substitute for all the delays applied to these activities in the models where the work is carried out by the main contractor. These are the delays related to materials, plant, equipment, temporary work and labour flows. A comparison of the subcontractor delays and the delays they replace in the models should help to explain how the results were obtained.

To start with, the comparison of these delays can be made at activity level. At activity level, there is only one subcontractor delay for a subcontracted activity, which substitutes for one or more delays in the equivalent main contractor model. Figure 6-23 below shows an example of an activity with the delays when carried out by the main contractor and with the delay when subcontracted. It can be seen that when the activity is subcontracted, the several delays in figure 6-23a are replaced by a single subcontractor delay (figure 6-23b).

This substitution will change the impact on the activity, which can be estimated by multiplying the probability of occurring by the extent of delay (most likely) of each delay. In figure 6-23a, where this activity is carried out by the main contractor, there are two delays in series and four delays in parallel. Therefore, the total impact of these delays on the activity is the sum of the impact of the two delays in series, plus whichever of the parallel delays has the biggest impact. The estimated impact on this activity is 4.4 days, while in figure 6-23b, where the work is subcontracted, the estimated impact of the single subcontractor delay is 0.8 days. Table 6-12 below shows the calculations of the impact of these delays on the activity and how they compare.



a. The activity is carried out by the main contractor



b. The activity is subcontracted

Figure 6-23 Comparing delays which are replaced by a subcontractor delay

Table 6-12 Comparing the estimated delays on activity *Substructure brickwork/blockwork* when carried out by the main contractor and when subcontracted

The activity is carried out by the main contractor				The activity is subcontracted			
Delays	Prob (%)	Most likely (days)	Impact (days)	Delays	Prob (%)	Most likely (days)	Impact (days)
Difficulty in finding materials in the market	14	12	1.68	SC: Bricks/blockwork	11	7	0.8
Late delivery	7	5	0.35				
Delivery with wrong specs *	9	7	-				
Materials damaged on arrival*	6	13	-				
Delivery with insufficient quantity*	15	6	-				
Skill shortages: Bricklayers*	26	9	2.34				
Estimated total impact on activity			**4.4**	**Estimated total impact on activity**			**0.8**

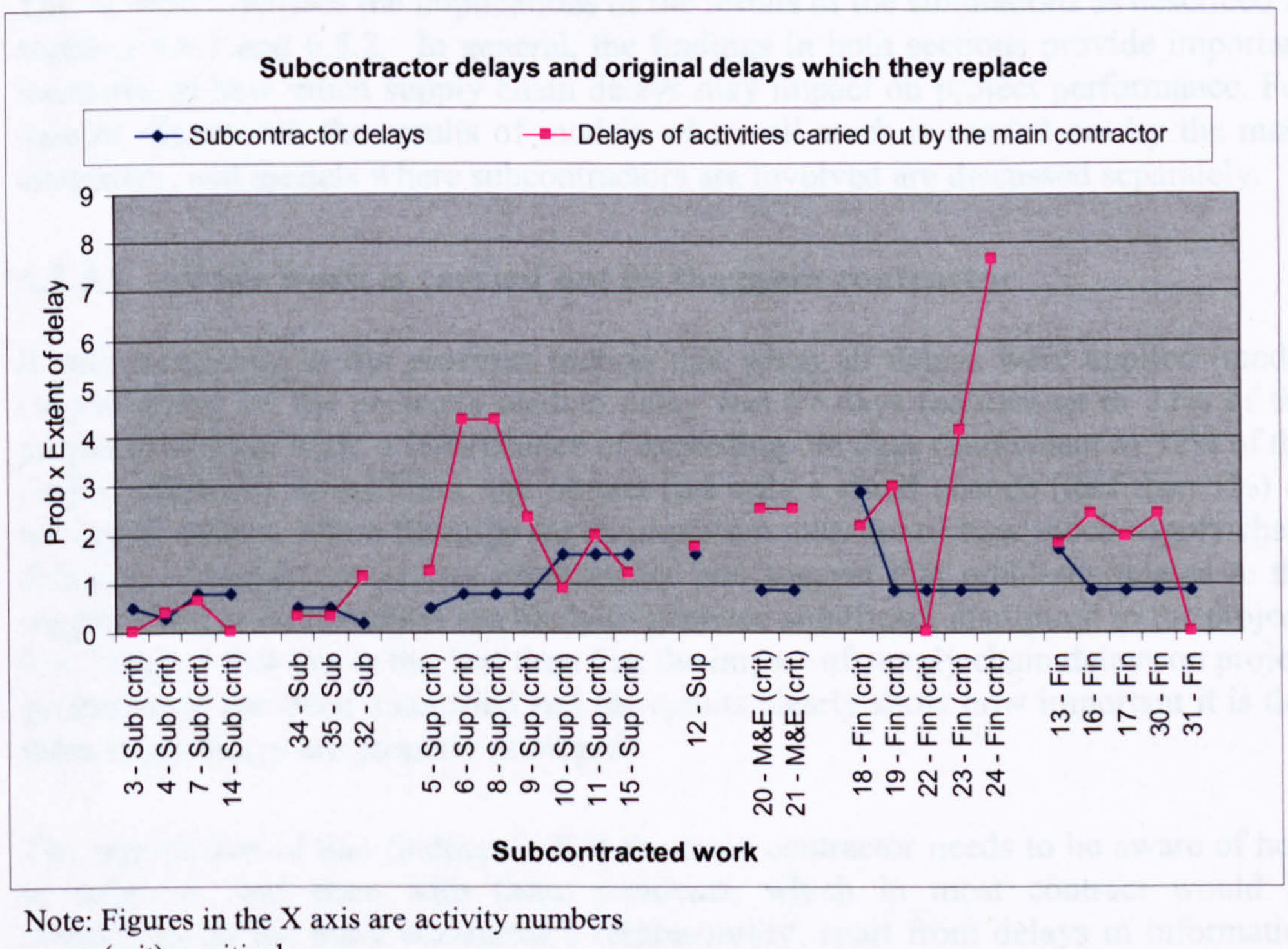
Note: * = Delays in parallel position

It can be seen that on this activity the subcontractor delay has less impact than the combined main contractor delays. In other words, subcontracting this activity would reduce the potential delays on this activity. For other activities in the network, this same approach can be used to compare subcontractor and main contractor delays.

Using this same method, the comparison of subcontractor delays and the original delays they replace in subcontracted activities is summarised in figure 6-24 below. This summary was achieved by comparing the delays in model (1b) with the subcontractor delays in model (16), as both models have the most comphrensive range

of each type of delays to compare (The details of this comparison can be seen in the appendix C6). Here, the subcontractor delays are classified under the headings substructure (sub), superstructure (sup), M&E (M&E) and finishing work (fin). It can be seen that the majority of subcontractor delays have less impact on the activities they affect than the original delays they replaced. As mentioned in the previous section, the original critical path of the CPM network remains critical for most of the simulations. This means that the subcontractor delays on the critical path will be the main source of delays on the project.

The fact that the impact of these subcontractor delays on the subcontracted activities, is generally lower than the impact of the delays they replaced, is the likely explanation of how the results of the simulations in models (11b), (13b), (14b), (15b) were achieved. In these models, subcontracting as much of the work as possible (model 11b), subcontracting superstructure work (model 13b), M&E work (model 14b), or finishing work (model 15b) resulted in lower median delays than the median delay of model 1, where all work is carried out by the main contractor. In model 12b, where the substructure work is subcontracted, the median delay was slightly higher than that in model 1b. This is indicated in figure 6-24, where the impact of two out of four subcontractor delays on the critical path (i.e. activities 3 and 14) are higher than the delays they replaced.



Note: Figures in the X axis are activity numbers
(crit) = critical

Figure 6-24 Comparing subcontractor delays with delays they are replaced in the models

In general, the explanation regarding subcontractor delays for models (11b)-(15b) in this section also applies to models (16)-(20), as subcontractor delays are also applied in these models. However, it should be noted that they are slightly different from

models (11b)-(15b). While in models (11b)-(15b), the subcontractor delays are applied with the rest of the activities attracting main contractor delays, in models (16)-(20) delays are only applied to subcontracted activities and no delays are applied to activities carried out by the main contractor. This means that models (16)-(20) have far fewer delays (the C factor). As explained in the previous section (6.5.3.1), it is recognised that when the values of C are low, the median delays can also be expected to be low.

To conclude, comparisons of the estimated impact of subcontractor delays and the main contractor delays on activities can be used to explain the results of models 11b-20. When the impact of most of the subcontractor delays is lower than the impact of the main contractor delays they replace, it can be expected that the median delay of the project which subcontracts some of the work will be lower than the equivalent project where all work is carried out by the main contractor. In models (16)-(20), however, the number of delays on the critical path (the C factor) also has a significant effect on the results of the simulations.

6.5.4 Implications of the results

This section discusses the implications of the results of the simulations as described in sections 6.5.1 and 6.5.2. In general, the findings in both sections provide important measures of how much supply chain delays may impact on project performance. For ease of discussion, the results of models where all work is carried out by the main contractor, and models where subcontractors are involved are discussed separately.

6.5.4.1 All the work is carried out by the main contractor

It was mentioned in the previous section that when all delays were applied (model (1b) in group 1), the project's median delay was 67 days (equivalent to 22% of the project duration), with a 10% chance of exceeding 96 days (equivalent to 32% of the project duration). In addition, the project had only a small chance (less than 1%) of having no delays. These findings are an important measure of how much supply chain delays may impact on project performance and suggest that problems related to the supply chain in construction are likely to generate significant disruption to the project. It is believed that this is the first time that the impact of supply chain delays on project performance has been quantified and the results clearly show how important it is that these large delays are properly managed.

The implication of this findings is that the main contractor needs to be aware of how to indentify and cope with these problems, which in most contract would be categorised as the main contractor's responsibility, apart from delays in information flow, which are likely to be the responsibility of the client. If the delays are not properly managed, the main contractor may have to pay liquidated damages should the project not finish on time.

To manage these supply chain delays better, either by making allowances in the programme, by monitoring their durations and responding to minimise, or more likely

both, the main contractor would be best advised to focus especially on those supply chain delays with the biggest impact on the project. The results of models (2), (3) and (4) in group 2 suggest that the biggest impact on the project was due to delays in material flow, followed by labour flow, information flow and 'plant, equipment and temporary work' flow. Of course, this ranking is true for the selected project and might be assumed to be similarly true for other such projects (medium-sized low-rise buildings). For other types of project, the contribution of these flows to the performance of the project may have to be revisited.

The project's median delay due to supply chain delays in the material flow is 25 days, with a 10% chance of delaying the project by 48 days. This finding is consistent with the fact that in a typical building project, there are likely to be hundreds of different kinds of materials to be used in the project. The kinds of materials in this type of project can be very complicated, especially when compared to typical civil engineering projects (e.g. roads, bridges, dams) where only a few different types of materials are needed, but in large quantities. All in all, the complexity of the material flow can clearly become a large problem in such a typical building project.

In this research, more specific problems related to materials were also identified, i.e. late delivery of materials, delivery with wrong specifications, materials damaged on arrival, materials delivered with insufficient quantity, and materials difficult to find. The results suggest that when each of these delays was applied individually, the first four delays did not result in a significant impact on the project. However, the biggest impact was due to difficulties in finding materials (sourcing), which resulted in a median delay on the project of 14 days (equivalent to 5% of the project duration), with a 10% chance of exceeding 35 days (equivalent to 12 % of the project duration). It can be seen that although these five types of delays in material flow resulted in the project's median delay of 25 days when applied all at once, only delays due to difficulties in finding materials had a very significant impact on the project when applied individually. This can be explained as follows.

When these five delays are compared, it can be seen that the main contractor actually has more control over the first four delays. He is in a good position and has power over the suppliers to request them to limit these problems from happening. This means that the delays are more controllable by the main contractor, hence the impact can be minimised. On the other hand, the main contractor is generally not in a position to influence the client or the architect regarding special materials to be used in the project, which may not be easy to find in the market, or may need a long lead time to procure them. Hence, this may result in longer delays to the activity that needs them.

As with material flow, labour flow also poses a significant problem to the project with a median delay of 19 days, 10% chance of exceeding 35 days and only a 3% chance of there being no delays. In this typical building project, there are many work items with various types of materials which require specific skills from the workforce, e.g. bricklayers, plasterer, joiners, plumbers, etc. Referring back to the survey results (table 4-7), it can be seen that joiners, plumbers and electricians are among the top skills with a high probability of shortages during the construction period (28%), while concrete gangs and labourers are among the skills with the least probability of a shortage (10% and 11%). It should be borne in mind that for other types of projects,

where a smaller variety of skills are needed, (e.g. civil engineering projects), the results might be different.

At the time this data was obtained in the UK, January – April 2006, it was reported there had been a lack of skills in construction in the UK (Campbell, 2006). It was also reported that many foreign workers from eastern Europe had filled this demand which could not be fulfilled by local labour. All in all, the simulation results represent this situation and show that labour flow is one of the significant factors that can impact on project performance. Hence, it should become the main contractor's concern after material flow.

Delays in the information flow rank third in terms of the extent of impact on the project, with the project's median delay of 17 days (equivalent to 6% of the project duration), and a 10% chance of exceeding 32 days (equivalent to 11% of the project duration). These figures are just slightly lower than the extent of impact due to delays in the labour flow. Problems in information flow include obtaining information, approval, drawings, etc., from a client or architect. These can be a very critical problem, since an activity often cannot start without them. Quite often, these problems are beyond the main contractor's capability to control, unlike the problems in material flow, where the main contractor can use his superior position over suppliers when they do not perform well, in this flow, the main contractor is dependent on others to provide the information needed. The site manager of WBHS project (one of the two projects visited) said that although delays in obtaining information from the client were not unusual, he could not put too much pressure on the client to obtain the information needed, as he stressed the importance of maintaining a good relationship with his client. Hence, he was torn between putting pressure on the client to get the information he needed and keeping good relationships, and the need to maintain friendly terms often won out. It should be recognised, however, that in contractual terms, a contractor is likely to be able to claim for extra costs and time for this type of delay, whereas all the other supply chain delays in the model are typically at the contractor's risk.

Among the four flows, 'plant, equipment and temporary work' flow seems to have the least impact on project performance with the project's median delay of only 5 days (equivalent to 2% of the project duration), with a 10% chance of delaying the project by 13 days (equivalent to 4% of the project duration). The frequency with which the project was delayed is only 56%. These low results can be understood as this study was carried out for a typical school building project, which in nature do not require a lot of heavy plant, temporary work nor large-scale earth-moving. These results may also suggest that there are no significant problems regarding the supply of plant, equipment and temporary work in the industry for such typical projects. It should be noted that for larger scale building projects or for other types of projects, such as civil engineering work, where a lot more plant, equipment and temporary work are needed, the impact could be much higher.

6.5.4.2 Subcontractors are used to carry out activities that are normally subcontracted

It was learnt from section 6.5.2 that subcontracting as much as possible of the work that is normally subcontracted resulted in less delays to the project than when all work is carried out solely by the main contractor. There was a significant reduction of delays from 67 days to 37 days; equivalent to a 45% reduction. There was also a substantial reduction of delays when subcontracting superstructure or finishing work by 17 and 14 days (equivalent to 25% and 21% reduction). However, subcontracting substructure or M&E work did not make a significant difference in terms of reducing delays.

These findings suggest that subcontracting work which is normally subcontracted, can benefit the main contractor. They may also justify the general practice of subcontracting large amount of work in building projects as a way of reducing the risks of project delays. In such projects, there is a lot of specific work which needs special equipment and expertise. This applies, as suggested by the results, particularly to superstructure and finishing work. Subcontractors are the ones who usually have the resources and expertise to carry out such specific work most efficiently. Their experience of undertaking the same work over the years make them more specialised, efficient and cost-effective. For this reason, although a main contractor may have the resources to carry out the work itself, it may not be the best option to do so. Once work is subcontracted, a subcontractor is responsible for finishing it. From the risk management perspective, it can also be seen as a way of transferring as well as sharing risks between the main contractor and its subcontractors. In addition, while the temporary nature of the project may cause the main contractor difficulties in finding the right local suppliers for its project, the local subcontractors may already have their own suppliers who have worked with them for years. All these, in turn, may reduce the risks of experiencing delays on the project.

As for subcontracting substructure or M&E work, it should be borne in mind that this project is medium-sized and does not involve a lot of substructure work (including groundwork) and M&E work. It can be seen from section 6.5.3 that there are only 4 and 2 activities respectively along the critical path that can be delayed by delays in these two categories. Hence, the impact can be expected not to be significant. For larger building projects or other types of projects, e.g. civil engineering projects, which involve a lot of substructure work or highly serviced buildings, which require a lot of M&E work, the results may well be different.

Chapter 7
Conclusions and Recommendations

This is the final chapter which concludes the work and presents some recommendations for the main contractors and further research. It consists of two sections:

7.1 **Conclusions**: This section will summarise the main results of the research to fulfil the aims and objectives of this study, as stated in the introduction.

7.2 **Recommendations**: There are a number of recommendations for the construction industry and also recommendations for further research.

7.1 Conclusions

The followings are the main conclusions of this research based on the results and discussions presented in chapter 6. It should be noted that these conclusions were drawn from simulation models with some simplifications, e.g. no rescheduling was allowed on the project, and delays were assumed to be independent. Provided these simplifications are accepted, the following conclusions can be made.

1. This research is arguably the first attempt to quantify the impact of supply chain delays on the performance of a building project. The results show that when all work was carried out by the main contractor and all delays were applied, the project's median delay was 67 days (equivalent to 22% of the project duration), with a 10% chance of exceeding 96 days (equivalent to 32% of the project duration). In addition, the project had only a small chance (less than 1%) of having no delays. These findings are an important measure of how much supply chain delays may impact on project performance and suggest that problems related to the supply chain in construction are likely to generate significant disruption to the project. It should be recognised that the results were obtained by simulating the effect of delays on a specific CPM network representing a typical medium-sized, low-rise building project, as the research design made it essential that a specific project type be adopted. Therefore, the results discussed above, and also the rest of the conclusions in this section, are true for the selected project and might be assumed to be similarly true for other such projects (medium-sized low-rise buildings). Clearly, factors such types of materials, use of plant, complexity of construction and extent of subcontracting will mean that other types project will be affected differently by supply chain delays. Nevertheless, this research provides a platform for future investigations of the impact of supply chain delays on projects, that are different in their nature and characteristics.

2. When all work on the project was carried out by the main contractor, it was learnt that material flow caused the biggest impact, followed by labour flow, information

flow, and 'plant, equipment and temporary work' flow. The project's median delay due to delays in material flow was 25 days and there was also a 10% chance of delaying the project by 48 days (equivalent to 16% of the project duration). Delays due to labour flow and information flow were not significantly different, i.e. 19 and 17 days (both were equivalent to 6% of the project duration) with a 10% chance of exceeding 35 and 32 days respectively (equivalent to 12% and 11% of the project duration). Finally, the lowest impact was due to problems related to 'plant, equipment and temporary work' flow of 5 days (equivalent to 2% of the project duration), with a 10% chance of delaying the project by 13 days (equivalent to 4% of the project duration). For the individual models that incorporated these flows, the chance of the project not being delayed was 6% or less, with the exception of 'plant, equipment and temporary work' flow, where the chance was 44%.

3. In this research, more specific problems related to materials were also identified, i.e. late delivery of materials, delivery with wrong specifications, materials damaged on arrival, materials delivered with insufficient quantity, and materials difficult to find. The results suggest that when each of these delays was applied individually, the biggest impact was due to difficulties in finding materials (sourcing), which resulted in a median delay on the project of 14 days (equivalent to 5% of the project duration), with a 10% chance of exceeding 35 days (equivalent to 12 % of the project duration). There was also a 19% chance of having no delays. The rest, however, did not result in a significant impact on the project, with median delays of 0-1 day, although there was also a 10% chance of delaying the project by 7 and 12 days (equivalent to 2-4% of the project duration), and 45-79% chance of having no delays on the project. The pre-eminence of the delay due to sourcing was an unexpected result, but one that might be explained when it is recognised that this is the one materials-related delay where the influence of good supply chain management may have little effect. If the materials in question are not readily available, there may be little the contractor can do to improve the situation. It would be very interesting to determine whether this is seen more widely as the most important materials delay.

4. When subcontractors were used for the activities that are normally subcontracted, there was a significant reduction of median delays from 67 to 37 days (equivalent to a 45% reduction), and also a 10% chance of reduction of delays from 96 to 58 days (equivalent to a 40% reduction). The project had only a small chance (less than 1%) of having no delays. These findings suggest that subcontracting work which is normally subcontracted can give considerable benefits to the main contractor. Of course, subcontractors might be expected to work more efficiently and cost-effectively, and have greater control of possible delays, because of their years of experience and particular knowledge and skills focused on their specialist areas of work. Although this result might therefore have been expected, this work reinforces the view that using subcontractors can improve the performance of projects and gives some quantification of the benefits. As with the previous conclusion, the applicability of this result across the industry would be interesting to test.

5. When only one particular part of work was subcontracted at a time, subcontracting superstructure or finishing work reduced the extent of delays by 17 and 14 days

respectively (equivalent to 25% and 21% reduction). Subcontracting substructure or M&E work, however, did not make a significant difference in terms of reducing project delays, with only 1-3% reduction of the extent of delays. These results seem to be a reflection of the nature of the typical medium-size low-rise building project which involves a lot of superstructure and finishing work and less substructure and M&E work.

6. In an attempt to realistically represent the real life situation, 2 versions of the models were prepared, i.e. the optimistic and pessimistic versions. The optimistic version represent a best case scenario in which delays on a project occur simultaneously, and the pessimistic version represents a worst case scenario when these delays occur consecutively. In the models, delays in optimistic versions were arranged in parallel, while the delays in the pessimistic models were positioned in series, as long as the logic allowed this to happen. The results of the optimistic and pessimistic models were very similar. Although they could not be proven to be statistically the same due to the large datasets (n=20000), visual comparison of the graphs of both models show that both are indeed very similar, hence, either can be used.

7. Providing time buffers for activities, in theory, would be expected to reduce the impact of delays on the project, as they may absorb delays. In this research, the time buffers were meant to absorb delays from the late delivery of materials. The results, however, show that median delays of the models both with and without time buffers, were not significantly different. The provision of time buffers on material delivery did not significantly improve project performance and only affected the extent of delays on the projects by less than 1% of the project duration.

7.2 Recommendations

7.2.1 Recommendations for the industry

The following are recommendations for the construction industry based on the results of this research:

1. It is evident that different versions of the research model could be produced to quantify supply chain delay impacts on the different types of project typically found in the industry, and it is believed that this would help contractors to isolate and focus on major sources of delay. However, as this kind of work is mainly carried out by researchers and not practitioners, a more helpful outcome would be for project participants to make themselves aware of the main findings of this work. Although they may be involved in quite a different project to the one studied here, it is believed that understanding the different types of supply chain delay and relating them to the quantified results for this project would help them to appreciate better the management action they may need to consider for their own projects.

2. It has long been recognised that involving contractors at an early stage in the project cycle should have a positive impact on project success. Indeed, the Highway Agency are now adopting an "Early Contractor Involvement" procurement route for many of their projects. One of the main ways in which contractors can influence a project is to offer advice on buildability and choice of materials; the current research provides future support for this procurement option by identifying and quantifying the sourcing of materials as the main cause of materials delay.

3. The impact of delays in labour flow on the project ranks second after material flow. Although scarcity of skills can be overcome by using the skills from the increasing number of migrant workers in the UK (e.g. from Eastern Europe), an alternative solution of using more prefabricated materials might be worth considering. It can be argued that using more prefabricated materials can reduce the dependency of contractors upon some of these skills that can be difficult to provide on construction sites. For example, the use of prefabricated cladding may replace the needs of bricklayers to build brick walls. In comparison with cast in place, the use of prefabricated concrete floors can also reduce the need for site-based labour and the project may also benefit from faster installation of these prefabricated materials.

7.2.2 Recommendations for further research

The following are a number of recommendations for future research.

1. The results of the simulations were obtained using models and data in the context of typical schools or similar building projects. A question should then be asked as to whether these results or models might be applied to other types of projects. This could be done by using different CPM networks for the different projects and modifying the types and number of supply chain delays to suit the characteristic of those projects. For example, in typical civil engineering projects, there may be fewer types of materials, but in larger quantities. They may also involve a lot of earth moving which will need large amount of plant, equipment and temporary works.

2. Due to the limited data available, the impact of the supply chain delays in this research was measured in terms of time only. Further work could be developed to recognise the cost implications of supply chain delays on the project. These are mainly the main contractor's costs which are incurred due to the extra time he has to spend on site due to delays, and/or possible liquidated damages to pay. It should be borne in mind that delays in information flow are not likely to be included in the main contractor's costs as these should be the employer's responsibility.

3. Only one type of information delay was used in the simulations as it was thought that all the different kinds of delays in information could be represented by this single category. In reality, however, a single activity can be delayed by various types of information delay and the extent of these delays could vary significantly. Delays in obtaining permissions from local authorities, for example, might be expected to be longer than delays in getting drawings or specifications from the

architect or client. It would be interesting for future work if these delays could be recognised and made more specific to better represent the project's complexity in information flow.

4. It was found in this research that subcontracting most of the work that is normally subcontracted resulted in less delay to the project than when all the work was carried out by the main contractor. Although this result supports what might be expected, it would still be very interesting to check whether this conclusion holds across the construction industry. A similar check could also be made on whether the main material delay comes from difficulties in sourcing unusual materials.

5. While rescheduling of activities in a project is common practice, the development of the models in this research do not permit such practice. It is recommended that the capability of rescheduling activities be included in future versions to make the simulation models more realistic.

6. Supply chain delays in the simulation models were assumed to be independent. In reality, however, there are delays which are dependent, meaning that one delay can lead to another delay. Future work should include this in the models.

7. The results of this research were obtained from hypothetical simulation of supply chain delays on a typical CPM network. It would be valuable for future work if these results can be validated externally by comparing them to real projects. It should be borne in mind, however, that while this research focuses on supply chain delays only, delays in real projects may cover all types of delays. Provided that these projects have good record keeping practices, non supply chain delays could be excluded from the projects, so that the total delays would become comparable to the results of this research.

References

(1995) *Concise Oxford Dictionary 9th edition.*

(2004) 'Council of Logistics management (CLM)', *www.clm1.org*.

AbouRizk, S. M. and Halpin, D. W. (1992) 'Statistical properties of construction duration data', *Journal of Construction Engineering and Management, ASCE,* 118, (3), pp. 525-544.

Agapiou, A., Flanagan, R., Norman, G. and Notman, D. (1998) 'The changing role of builders merchants in the construction supply chain', *Construction Management and Economics,* 16, pp. 351-361.

AIAA. (1998) *Guide for the verification and validation of computational fluid dynamics simulations, AIAA-G-077-1998.* Reston, VA:

Akintoye, A. (1995) 'Just-in-Time aplication and implementation for building material management', *Construction Management and Economics,* 13, pp. 105-113.

Al-Hammad, A. (1993) 'Factors affecting the relationship between contractors and their sub-contractors in Saudi Arabia', *Building Research and Information,* 21, (5), pp. 269-73.

Al-Khalil, M., Assaf, S., Al-Faraj, T. and Al-Darweesh, A. (2004) 'Measuring Effectiveness of Materials Management for Industrial Projects', *Journal of Management in Engineering (ASCE),* 20, (3).

Al-Momani, A. H. (2000) 'Construction delay: a quantitative analysis', *International Journal of Project Management,* 18, pp. 51-59.

Alarcon, L. F. (1997) 'Modelling waste and performance in construction', in Alarcón, L. F.(ed), *Lean Construction.*Rotherdam, The Netherland: A.A. Alkema.

Alarcón, L. F., Rivas, R. and Serpell, A. (1999) *'Evaluation and Improvement of the Procurement Process in Construction Projects', in* Proceedings IGLC-7 26-28 July.University of California, Berkeley, CA, USA:

Alkass, S., Mazerolle, M., Tribaldos, E. and Harris, F. (1995) 'Computer aided construction delay analysis and claims preparation', *Construction Managemnt and Economics,* 13, pp. 335-352.

Ammar, M. A. and Mohieldin, Y. A. (2002) 'Resource constrained project scheduling using simulation', *Construction Management and Economics,* 20, pp. 323–330.

Arbulu, R. and Ballard, G. (2004) *'Lean supply systems in construction', in* Proceeding IGLC10, 12th Annual conference on Lean Construction.Denmark:

Arbulu, R. and Tommelein, I. D. (2002a) '*Contributors to lead time in construction supply chains: Case of pipe supports used in power plants', in* Proceedings of the 2002 Winter Simulation Conference.

Arbulu, R. J. and Tommelein, I. D. (2002b) '*Value stream analysis of construction supply chains: Case study on pipe supported used in power plants', in* Proceedings IGLC-10, August 2002.Gramado, Brazil:

Arnold, J. R. T. (1991) *Introduction to materials management.* London: Prentice-Hall International (UK) Limited.

Assaf, S. A., Al-Khalil, M. and Al-Hazmi, M. (1995) 'Causes of delay in large building construction projects', *Journal of Management in Engineering (ASCE),* 11, (2), pp. 45-50.

Baldry, D. (1996) 'Client benchmarking of contractor performance', in Langford, D. A. and Retik, A.(eds) *The organization and management of construction : Shaping theory and practice.* Vol. 2 E & FN Spon.

Ballard, G. and Howell, G. (1998) '*What kind of production is construction?' in* Proceeding IGLC.

Banwell, G. H. (1964) *The Banwell report.* HMSO.

Beamon, B. M. (1999) 'Measuring supply chain performance', *International Journal of Operations & Production Management,* 19, (3), pp. 275-292.

Bechtel, C. and Yayaram, J. (1997) 'Supply chain management: a strategic perspective', *International journal of logistics management,* 8, (1), pp. 15-34.

Berry, D., Towill, D. R. and Wadsley, N. (1994) 'Supply chain management in the electronics product industry', *International Journal of Physical Distribution & Logistics Management,* 24, (10), pp. 20-32.

Bhatnagar, R. and Sohal, A. S. (2004) 'Supply chain competitiveness: measuring the impact of location factors, uncertainty and manufacturing practices', *Article in Press, Technovation,* xx, (xxx-xxx), pp. 1-14.

Bresnen, M. J. and Haslam, C. O. (1991) 'Construction industry clients: A survey of their attributes and project management practices', *Construction Managemnt and Economics,* 9, pp. 327-342.

Bresnen, M. J. and Marshall, N. (1999) 'Partnering in construction: a critical review of issues, problems and dilemmas', *Construction Management and Economics,* 18, pp. 229-237.

Briscoe, G., Dainty, A. R. J. and Millett, S. (2001) 'Construction supply chain partnerships: skills, knowledge and attitudinal requirements', *European Journal of Purchasing & Supply Management,* 7, pp. 243-255.

Briscoe, G. H., Dainty, A. R. J., Millett, S. J. and Neale, R. H. (2004) 'Client-led strategies for construction supply chain improvement', *Construction Management and Economics,* 22, (February), pp. 193-201.

Burt, D. (1984) *Proactive Procurement.* Englewood, Cliffs Prentice-Hall.

Caldwell, N. and Down, S. (1997) "Faking it' in supply chain relationships', *Management research news,* 20, (2), pp. 53-61.

Campbell, F. (2006) *Skills shortages in the UK construction industry. Survey 2006.* CIOB

Cavinato, J. L. (1992) 'A total cost/value model for supply chain competitiveness', *Journal of business logistics,* 13, (2), pp. 285-301.

Chan, D. W. M. and Kumaraswamy, M. M. (1997) 'A comparative study of causes of time overruns in Hong Kong construction projects', *International Journal of Project Management,* 15, (1), pp. 55-63.

Christian, J. and Hachey, D. (1995) 'Effects of delay times on production rates in construction', *Journal of Construction Engineering and Management,* 121, (1), pp. 20-26.

Christopher, M. (1992) *Logistics and supply chain management: strategies for reducing costs and improving service.* London, UK: Pitman Publishing.

Christopher, M. (1998) *Logistics and supply chain management: Strategies for reducing cost and improving service.* London: Financial Times Pitman Publishing.

Chung, C. A. (2004) *Simulation modeling handbook: A practical approach.* CRC Press.

Cohen, M. A. and Lee, H. L. (1990) 'Out of touch with customer needs? Spare parts and after sales service.' *Sloan Management Review,* 31, (2), pp. 56-66.

Collis, J. and Hussey, R. (2003) *Business research. A practical guide for undergraduate and postgraduate students.* Palgrave Macmillan.

Conlin, J. and Retik, A. (1997) 'The applicability of project management software and advanced IT techniques in construction delays mitigation', *International Journal of Project Management,* 15, (2), pp. 107-120.

Cooper, M. C. and Ellram, L. M. (1993) 'Characteristics of supply chain management and the implications for purchasing and logistics strategy,' *International journal of logistics management,,* 4, (2), pp. 13-24.

Cooper, M. C., Lambert, D. M. and Pagh, J. D. (1997) 'Supply chain management: more than a new name for logistics', *International journal of logistics management,* 8, (1), pp. 1-13.

Cox, A. and Ireland, P. (2002) 'Managing construction supply chains: the common sense approach', *Engineering, Construction and Architectural Management,* 9, (5/6), pp. 409-418.

Cox, A., Ireland, P. and Towsend, M. (2006) *Managing in construction supply chains and market.* London: Thomas Telford.

Cox, A. and Townsend, M. (1998) *Strategic procurement in construction.* London: Thomas Telford Publishing.

Creswell, J. W. (2003) *Research design: Qualitative, quantitative and mixed methods approaches.* Thousand Oaks, California: Sage Publication, Inc.

Croom, S., Romano, P. and Giannakis, M. (2000) 'Supply chain management; an analytical framework for critical literature review', *European Journal of Purchasing & Supply Management,* 6, pp. 67-83.

Davis, T. (1993) 'Effective supply chain management,' *Sloan management review,* 34, (4), pp. 35-46.

Denzin, N., K and Lincoln, Y. S. (1994) *The handbook of qualitative research.* Sage publications.

Denzin, N. K. (1970) *The research act: A theoretical introduction to sociological method.* Chicago: Aldine.

Dillman, D. A. (1991) 'The design and administration of mail surveys', *Annual Review of Sociology,* 17, pp. 225-249.

Dyer, J. H., Cho, D. S. and Chu, W. (1998) 'Strategic supplier segmentation:The next best practice in supply chain management.' *California Management Review* 40, (2), pp. 57-77.

Easterby-Smith, M., Thorpe, R. and Lowe, A. (1991) *Management Research: an Introduction.* London: Sage.

Edum-Fotwe, F. T., Thorpe, A. and McCaffer, R. (1999) *'Organisational relationships within the construction supply-chain', in* Proceedings of a Joint CIB Triennial Symposium.Cape Town:

Edum-Fotwe, F. T., Thorpe, A. and R. McCaffer, R. (2001) 'Information procurement practices of key actors in construction supply chains', *European Journal of Purchasing & Supply Management,* 7, pp. 155-164.

Elfving, J. A. (2003) *Exploration of opportunities to reduce lead times for engineered-to-order-products.* Unpublished PHD thesis thesis. University of California.

Ellram, L. M. (1990) 'The supplier selection decision in strategic partnerships', *Journal of purchasing and materials management,* 26, (4), pp. 8-14.

Ellram, L. M. (1991) 'Supply chain management: the industrial organization perspective', *International journal of physical distribution and logistics management,* 21, (1), pp. 13-22.

Ellram, L. M. (1996) 'The use of the case study method in logistics research', *Journal of Business Logistics,* 17, (2), pp. 93-137.

Ellram, L. M. and Cooper, M. C. (1990) 'Supply chain management partnerships, and the shipper-third party relationship', *International journal of logistics management,* 1, (2), pp. 1-10.

Farmer, D. H. (1995) 'Presentation at the NAPM International academic conference', in.

Formoso, C. T. and Revelo, V. H. (1996) 'Improving the material supply system in small sized building firms', in Langford, D. A. and Retik, A.(eds) *The organization and management of construction: shaping theory and practice.* Vol. 1 London, UK: E & FN Spon,pp 229-238.

Frimpong, Y. and Oluwoye, J. (2003) 'Significant factors causing delay and overruns in construction of groundwater projects in Ghana', *Journal of Construction Research,* 4, (2), pp. 175-187.

Gameson, R. N. (1992) *An investigation into the interaction between potential building clients ad construction professionals.* Unpublished PhD thesis thesis. University of Reading, UK.

Gameson, R. N. (1996) 'Client-professional communication during the early stages of project development', in Langford, D. A. and Retik, A.(eds) *The organization and management of construction : Shaping theory and practice.* Vol. 2 E & F Spon.

Ghurka, N. (2003) *Implementing supply chain "Best Practice" in the construction value system.* thesis. MIT.

Giunipero, L. C. and Brand, R. R. (1996) 'Purchasing's role in supply chain management', *International journal of logistics management,* 7, (1), pp. 29-37.

Greenwood, D. J. (2001) 'Subcontract procurement: are relationships changing?' *Construction Management and Economics,* 19, pp. 5-7.

Greenwood, D. J. (2004) 'The North Tyneside Partnering Agreement: a study of Strategic Partnering in the Public Sector. Research Report carried out for the Department of Trade and Industry by Northumbria University'.

Greenwood, D. J. (2005) 'Partnering Approaches and Supply Chain Relations', *Construction Information Quarterly, Chartered Institute of Building, Ascot,* 7, (1), pp. 3-5.

Guba, E. G. (1990) 'The alternative paradigm dialog', in Guba, E. G.(ed), *The paradigm dialog.*Newbury Park, CA: Sage publication, pp. 17-30.

Gunasekaran, A., Patel, C. and McGaughey, R. E. (2004) 'A framework for supply chain performance measurement', *International Journal of Production Economics,* 87, pp. 333-347.

Halpin, D. W. and Riggs, L. S. (1992) *Planning and Analysis of Construction Operations.* New York.: Wiley.

Handfield, R. B. and Nichols, E. L. (1999) *Introduction to Supply Chain Management.* Prentice-Hall, Englewood Cliffs, NJ.

Hensey, M. (1993) 'Essential tools of total quality management.' *Journal of Construction Engineering and Management, ASCE* 9, (4), pp. 329-39.

Hewitt, F. (1992) *'Supply chain integration', in* Annual conference proceedings.Oak Brook, USA: Council of Logistics Management.

Holmberg, S. (1997) *Measurements on an integrated supply chain.* Department of Engineering Logistics, Lund University.

Houlihan, J. B. (1985) 'International supply chain management', *International Journal of Physical Distribution & Materials Management,* 15, (1), pp. 22-38.

Houlihan, J. B. (1988) 'International supply chains: a new approach', *Management decisions,* 26, (3), pp. 13-19.

Johannson, L. (1994) 'How can a TQEM approach add value to your supply chain?' *Total quality environmental management,* 3, (4), pp. 521-530.

Jones, T. C. and Riley, D. W. (1985) 'Using inventory for competitive advantage through supply chain management', *International journal of physical distribution and materials management,* 15, (5), pp. 16-26.

Kadeforsi, A. (1999) ' *Client-contractor relations: How fairness considerations and interest influence contractor variation negotiations', in* Proceedings IGLC-7.

Kale, S. and Arditi, D. (2001) 'General contractors' relationships with subcontractors: a strategic asset', *Construction Management and Economics,* 19, pp. 541-549.

Kaming, P. F., Olomolaiye, P. O., Holt, G. D. and Harris, F. C. (1997) 'Factors influencing construction time and cost overruns on high-rise projects in Indonesia', *Construction Management and Economics* 15, pp. 83-94.

Kinnear, P. and Gray, C. D. (2004) *SPSS 12 Made Simple.* New York: Psychology Press Ltd.

Kopczak, L. R. (1997) 'Logistics partnership and supply chain restructuring: survey results from the US computer industry', *Production and Operations Management* 6, (3), pp. 226-247.

Kornelius, L. and Wamelink, J. W. F. (1998) 'The virtual corporation: learning from construction', *Supply Chain Management,* 3, (4), pp. 193-202.

Koushki, P. A., Al-Rashid, K. and Kartam, N. (2005) 'Delays and cost increases in the construction of private residential projects in Kuwait', *Construction Management and Economics,* 23, pp. 285-294.

Kumaraswamy, M. M. and Matthews, J. D. (2000) 'Improved subcontractor selection employing partnering principles', *Journal of Management in Engineering (ASCE),* 16, (3), pp. 47-57.

La londe, B. J. (1997) 'Supply chain management: Myth or reality?' *Supply Chain Management Review,* 1 (Spring), pp. 6-7.

La Londe, B. J. and Masters, J. M. (1994) 'Emerging logistics strategies: Blueprints for the next century', *International Journal of Physical Distribution & Logistics Management,* 24, (7), pp. 35-47.

Lambert, D. M. and Sharman, A. (1990) 'A customer-based competitive analysis for logistics decisions', *International Journal of Physical Distribution and Logistics Management* 20, (1), pp. 17-24.

Lambert, D. M., Stock, J. R. and Ellram, L. M. (1998) *Fundamentals of logistics management.* Boston: Irwin/McGraw-Hill.

Lamming, R. (1993) *Beyond partnership: strategies for innovation and lean supply.* New York, USA:: Prentice Hall.

Lamming, R. (1996) 'Squaring lean supply with supply chain management', *International journal of operations and production management,* 16, (2), pp. 183-196.

Langley, C. J., Jr. and Holcomb, M. C. (1992) 'Creating logistics customer value', *Journal of business logistics,* 13, (2), pp. 1-27.

Larson, E. (1995) 'Project partnering: Results of study of 280 construction project', *Journal of Management in Engineering (ASCE),* 11, (2), pp. 30-35.

Larson, P. D. and Halldorsson, A. (2004) 'Logistics versus supply chain management: An international survey', *International Journal of Logistics,* 7, (1), pp. 17-31.

Latham, S. M. (1994) *Constructing the Team: Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry.* London: HMSO.

Law, A. M. and Kelton, W. D. (2000) *Simulation modeling and analysis* McGraw Hill.

Lee, H. L. and Billington, C. (1992) 'Managing supply chain inventory: pitfalls and opportunities', *Sloan management review,* 33, (3), pp. 65-73.

Lee, H. L. and Ng, S. M. (1997) 'Introduction to the special issue on global supply chain management.' *Production and Operations Management* 6, (3), pp. 191-192.

Levy, D. L. (1995) 'International sourcing and supply chain stability', *Journal of International Business Studies,* 26, (2), pp. 343-360.

Lewis, T. M. and Atherley, B. A. (1996) 'Analysis of construction delays', in Langford, D. A. and Retik, A.(eds) *The organization and management of construction: shaping theory and practice*. Vol. 2 London, UK: E & FN Spon,pp 404-413.

London, K. (2001) '*Evolution of a supply chain firm constellation for innovative construction products: An instrumental case study', in* CIB World Building Congress.Wellington, New Zealand:

London, K. A. and Kenley, R. (2001) 'An industrial organization economic supply chain approach for the construction industry : a review', *Construction Management and Economics,* 19, pp. p.777-788.

Love, P. E. D., Irani, Z., Cheng, E. and Li, H. (2002) 'A model for supporting inter-organizational relations in the supply chain', *Engineering, Construction and Architectural Management,* 9, (1), pp. 2-15.

Manavazhia, M. R. and Adhikarib, D. K. (2002) 'Material and equipment procurement delays in highway projects in Nepal', *International Journal of Project Management* 20, pp. 627-632.

Marsh, L. E. and Finch, E. F. (1999) 'Using portable data files in the construction supply chain', *Building research and information,* 27, (3), pp. 127-139.

Matthews, J., Pellew, L., Phua, F. and Rowlinson, S. (2000) 'Quality relationships: partnering in the construction supply chain', *International Journal of Quality & Reliability Management,* 17, (45), pp. 493-510.

Matthews, J. D., Tyler, A. and Thorpe, T. (1996) 'Subcontracting - The subcontractor's view', in Langford, D. A. and Retik, A.(eds) *The organization and management of construction : Shaping theory and practice.* Vol. 2 E & EF Spon.

Mendenhall, W. and Sincich, T. (1988) *Statistics for the engineering and computer sciences.* London: Collier Macmillan Publishers.

Mentzer, J. T., Dewitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D. and Zacharia, Z. G. (2001) 'What is supply chain management?' in Mentzer, J. T.(ed), *Supply Chan Management.*California: Sage Publications, Inc.

Morris, J. and Imrie, R. (1993) 'Japanese style subcontracting: it's impact on European industries,' *Long range planning,* 26, (4), pp. 53-58.

Muya, M. (1999) *A systematic approach for improving construction materials logistics.* PhD thesis. Loughborough University.

Muya, M., Price, A. D. F. and Thorpe, A. (1999) '*Contractors' supplier management', in* Proceeding of a Joint CIB Triennial Symposium.Cape Town:

Naim, M. M. (1997) *Lesson for construction from manufacturing system engineering.*

Nassimbeni, G. (1998) 'Network structures and co-ordination mechanisms: a taxonomy', *International Journal of Operations and Production Management,* 18, (6), pp. 538-554.

Ndekuri, I. E. (1998) *Sub-contractor control, the key to succesful construction.* CIOB technical information service.

Neely, A., Gregory, M. and Platts, K. (1995) 'Performance measurement system design: a literature review and research agenda', *International Journal of Operations and Production Management,* 15, (4), pp. 80-116.

New, S. J. and Ramsay, J. (1995) '*Supply chains - corporate path to economic disaster? ' in* Fourth International IPSERA Conference.Birmingham:

Nicolini, D., Holti, R. and Smalley, M. (2001) 'Integrating project activities: the theory and practice of managing the supply chain through clusters', *Construction Management and Economics,* 19, pp. 37-47.

Nishiguchi, T. (1994) *Strategic Industrial Sourcing: The Japanese Advantage.* Oxford: Oxford University Press.

Novack, R. and Simco, S. W. (1991) 'The industrial procurement process: a supply chain perspective', *Journal of business logistics,* 12, (1), pp. 145-167.

Novack, R. A., Langley, C. J., Jr. and Rinehart, L. M. (1995) *Creating logistics value: Themes for the future.* Oak Brook, IL: Council of logistics management.

O'Brien, C. (2001) '*Enabling Technologies for Project Supply Chain Collaboration', in* NSF/ICIS Infrastructure and Information Technology Workshop.Arlington, VA, USA:

O'Brien, W. J. (1997) 'Construction supply-chains: Case study, integrated cost and performance analysis', in Alarcon, L.(ed), *Lean Construction.*Rotterdam: A.A.Balkema.

O'Brien, W. J. and Fischer, M. A. (1993) 'Construction supply-chain management: a research framework', *Civil Comp 93: Information Technology for Civil and Structural Engineers*, pp. 61-64.

Ogunlana, S. and Promkuntong, K. (1996) 'A survey of delays experienced in the construction of high-rise building projects in Bangkok, Thailand.' *International Journal of Project Management,* 14, (1), pp. 37-45.

Oliver, N., Delbridge, R., Jones, D. and Lowe, J. (1994) 'World class manufacturing: further evidence in the lean production debate', *British journal of management,,* 5, (June), pp. 53-63.

Oswald, T. H. and Burati, J. L. (1992) 'Guidelines for implementing Total Quality Management in the Engineering and Construction Industry', *Construction Industry Institute.*

Otto, A. and Kotzab, H. (2003) 'Does supply chain management really pay? Six perspectives to measure the performance of managing a supply chain', *European Journal of Operational Research,* 144, (2), pp. 306-320.

Packham, G., Thomas, B. and Miller, C. (2003) 'Partnering in the house building sector: a subcontractor's view', *International Journal of Project Management,* 21, pp. 327-332.

Pidd, M. (2004) *Computer simulation in management science* John Wiley & Sons, Ltd.

Plemmons, J. K. and Bell, L. C. (1995) 'Measuring effectiveness of materials management process', *Journal of Management in Engineering (ASCE),* 11, (6), pp. 26-32.

Proverbs, D. G. and Holt, G. D. (2000) 'Reducing construction costs: European best practice supply chain implications', *European Journal of Purchasing and Supply Management,* 6, pp. 149-158.

Rich, N. and Hines, P. (1997) 'Supply-chain management and time-based competition: the role of the supplier association', *International journal of physical distribution and logistics management,* 27, (3/4), pp. 210-225.

Rolstandas, A. (1995) *Performance Measurement: A Business Process Benchmarking Approach.* New York: Chapman & Hall.

Ross, D. F. (1998) *Competing through supply chain management.* New York: Chapman and Hall.

Roy, R., Brown, J. and Gaze, C. (2003) ' Re-engineering the construction process in the speculative house-building sector', *Construction Management and Economics,* 21, pp. pp. 137-146.

Rushton, A., Oxley, J. and Croucher, P. (2000) *The Handbook of Logistics and Distribution Management.* London:

Saad, M. (1996) 'Options for applying BPR in the Australian construction industry', *International Journal of Project Management,* 14, (6), pp. 379-385.

Salkind, N. J. (2000) *Statistics. For people who (Think They) hate statistics.* London: Sage Publications, Inc.

Sargent, R. G. (2003) '*Verification and validation of simulation models ', in* Chick, S., Sánchez, P. J., Ferrin, D. and Morrice, D. J.(eds), Proceedings of the 2003 Winter Simulation Conference.

Saunders, M. J. (1995) '*Chains, pipelines, networks and value stream: the role, nature and value of such metaphors in forming perceptions of the task of purchasing and supply management', in* First Worldwide Research Symposium on Purchasing and Supply Chain Management.Tempe, Arizona:

Scott, C. and Westbrook, R. (1991) 'New strategic tools for supply chain management', *International journal of physical distribution and logistics management,* 21, (1), pp. 23-33.

Scott, J. N., Bradley, D. A., Adelson, R. M., Pengelly, M. and Seward, D. W. (1995) 'Issues in the development of data flow simulation of construction sites: the pursuit of quality', *International Journal of Project Management,* 13, (5), pp. 535-339.

Scott, S., Greenwood, D. and Stitt, D. (2001) 'Improving Construction: Supply Chain Management', *Construction Information Quarterly,* 3, (3), pp. 1-4.

Serpell, A. (1997) 'Characterization of waste in building construction projects', in Alarcon, L. F.(ed), *Lean Construction.*Rotherdam, The Netherland: A.A. Alkema.

Shi, J. J. (2002) 'Three methods for verifying and validating the simulation of a construction operation', *Construction Management and Economics,* 20, pp. 483–491.

Silva, F. B. D. and Cardoso, F. F. (1999) 'Applicability of logistics management in lean construction: A case study approach in Brazilian building companies', *IGLC7.*

Sink, D. S. (1991) 'The role of measurement in achieving world class quality and productivity management', *Industrial Engineering,* June.

Slack, N., Chambers, S., Harland., C., Harrison, A. and Johnston, R. (1995) *Operations management.* London, UK: Pitman.

Smith, G. R. and Lin, Y.-B. (1996) 'Steel framing crew performance and variation', in Langford, D. A., Retik, A. (ed), *The organization and management of construction: shaping theory and practice.* Vol. 2 London, UK: E & FN Spon,pp 49-59.

Sobotka, A. (2000) 'Simulation modelling for logistics re-engineering in the construction company', *Construction Management and Economics,* 18, pp. 183-195.

Spivey, N. N. (1997) *The constructivist metaphor.* San Diego: Academic Press.

Stevens, G. C. (1990) 'Successful supply-chain management', *Management decisions,* 28, (8), pp. 25-30.

Stuckhart, G. (1995) *Construction Materials Management.* New York, NY: Marcel Dekker Inc.

Tah, J. H. M. and Carr, V. (2001) 'Towards a framework for project risk knowledge management in the construction supply chain', *Advances in Engineering Software,* 32, pp. 835-846.

Tan, K. C. (2001) 'A framework of supply chain management literature', *European Journal of Purchasing & Supply Management,* 7, pp. p. 39-48.

Tan, K. C., Kannan, V. R. and Handfield, R. B. (1998) 'Supply chain management: supplier performance and firm performance', *International Journal of Purchasing and Material Management,* 34, (3), pp. 2-9.

Tommelein, I. D. and Li, A. E. Y. (1999) '*Just-In-Time concrete delivery: Mapping alternatives for vertical supply chain integration', in* Proceeding IGLC 7.

Tommelein, I. D., Riley, D. and Hershauer, J. C. (2003) *Improving capital projects Supply Chain performance.* A research report to the Construction Industry Institute.

Tommelein, I. D. and Weissenberger, M. (1999) '*More Just-in-Time: Location of buffers in structural steel supply and construction processes', in* Proceeding IGLC 7.

Towill, D. R. (1996) 'Time compression and supply chain management - A Guided tour', *Supply Chain Management,* 1, (1), pp. 15-27.

Turner, J. R. (1993) 'Integrated supply chain management: what's wrong with this picture?' *Industrial engineering,,* 25, (12), pp. 52-55.

Venkataraman, R. (2004) 'Project supply chain management: Optimizing value: The way we manage the total supply chain', in Morris, P. W. G. and Pinto, J. K.(eds) *The Wiley Guide to Managing Projects.*New Jersey: John Wiley and Sons, Inc.

Vrijhoef, R. (1998) *Co-makership in construction : Towards construction supply chain management.* MSc Thesis thesis. Delft University of Tecnology, Delft.

Vrijhoef, R. and Koskela, L. (2000) 'The four roles of supply chain management in construction', *European Journal of Purchasing & Supply Management,* 6, pp. 169-178.

Vrijhoef, R., Koskela, L. and Howell, G. (1999) '*Understanding construction supply chains: an alternative interpretation', in* Proceeding IGLC 9.

Waggoner, D. B., Neely, A. D. and Kennerley, M. P. (1999) 'The forces that shape organizational performance measurement systems: an interdisciplinary review', *International Journal of Production Economics,* 60, pp. 53-60.

Wegelius-Lehtonen, T. (1995) '*Measuring and re-engineering logistics chains in the construction industry', in* Proceedings International Federation for Information Processing working conference on re-engineering the enterprise.Galway, Ireland: University College Galway:

Wegelius-Lehtonen, T. (2001) 'Performance measurement in construction logistics', *International Journal of Production Economics,* 69, pp. 107-116.

Wegelius-Lehtonen, T. and Pahkala, S. (1998) 'Developing material delivery process in cooperation: An application example of the construction industry', *International Journal of Production Economics,* 56-57, pp. 689-69.

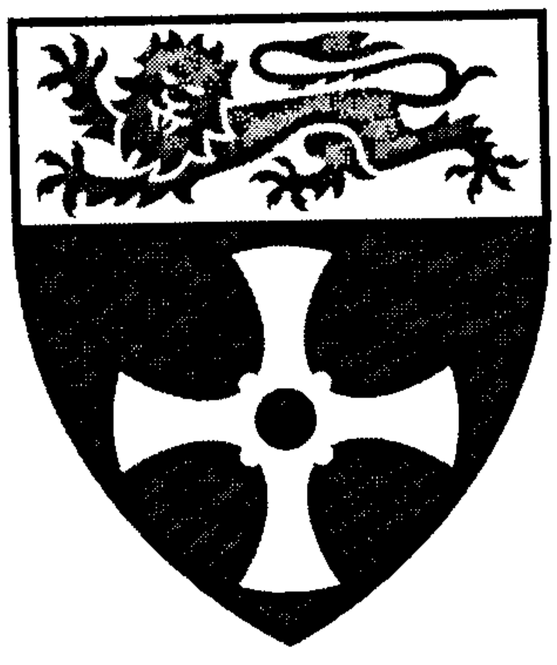
Williams, T. (2004) 'Why Monte Carlo Simulations of project networks can mislead', *Project Management Journal,* 35, (3), pp. 53-61.

Yammarino, F. J., Skinner, S. J. and Childers, T. L. (1991) 'Understanding mail survey response behavior: a meta-analysis', *Public Opinion Quarterly* 55, (4), pp. 613-39.

Yeo, K. T. and Ning, J. H. (2002) 'Integrating supply chain and critical chain concepts in engineer-procure-construct (EPC) projects', *International Journal of Project Management,* 20, pp. 253-262.

Yin, R. K. (1994) *Case study research: Design and methods.* Beverly Hills: Sage.

Yin, R. K. (2003) *Case Study Research: Design and Methods.* London: Sage.



Appendices

Appendix A1
List of Questions for Main Contractor

This preliminary survey aims at identifying supply chain management practice and its impact on site performance

The general questions below include;

A. Project characteristics
B. Subcontractors/suppliers selection
C. Contract
D. Site Performance
E. Customer satisfaction
F. Technical operation
G. Performance assessment of subcontractors/suppliers
H. Incentives for subcontractors/suppliers
I. Disputes, Partnering
J. Risk and Uncertainties
K. IT/internet
L. Main Problems
M. Degree of Involvement

A. Project characteristics:

For the projects operating from your company's office, please provide the following information:

1. (Project Size). What is the range of project's total budget?
2. (Project complexity) How many subcontractors and suppliers are normally involved in a project?
3. (Duration). How long normally is the duration of your projects?
4. (Specialty) What kind of projects do you construct?

B. Subcontractors/suppliers selection

1. What is the mechanism for Subcontractor/supplier selection?
2. What is the main consideration in selecting subcontractors/suppliers?
3. Which do you prefer, local or national suppliers/subcontractors? Why?
4. How do you know about the subcontractors/suppliers?

C. Contract

1. What kind of agreements (contracts) are normally used with sub contractors/suppliers?
2. Do you give subcontractors/suppliers the detail material specification before you make an order?

D. Site Performance

1. What system do you use to monitor the efficiency of your operation on site?
2. What is the impact of late materials delivery on site performance and how often does it happen?
3. Do you benchmark your site performance against other similar project in the same firm or other firms?

E. Customer satisfaction

1. Do you measure your customer satisfaction?
2. How do you measure it?

F. Technical operation

1. Do you buy the material as you need it or make an arrangement with the supplier for the full quantity, and set the delivery schedule (dates and quantities)
2. Do you ever buy and stockpile materials off-site to use them on-site at a later stage?
3. Do you check the materials/the work of subcontractors thoroughly?

4. Who is responsible for unloading the materials from the truck to the storage area on site; the supplier or you?
5. Do you ever disapprove materials which do not meet the specification? In your opinion, what is the main reason this happens?

G. Performance assessment of subcontractors/suppliers

1. How do you assess the performance of subcontractors/suppliers?

H. Incentives for subcontractors/suppliers

1. Is there any incentive (reward system) to encourage good performance from subcontractors/suppliers?

I. Disputes

1. Have you ever had disputes with subcontractors/suppliers?
2. In what areas do most disputes occur?
3. How do you resolve the disputes?

J. Partnering

1. Do you build long term relationships with preferred subcontractor/suppliers?
2. What advantages are there for long term relationships?
3. Do you treat firms with whom you have long time relationships differently? (For example, by giving them first chance to bid?)
4. Of your suppliers, what percentage are one-off and what percentage are regular repeat business?

K. Risk and Uncertainties

1. If the material delivery from the supplier is late, so that the work on site is delayed, who is responsible?
2. Is there any penalty in the contract for subcontractors/suppliers for late delivery? Do you pursue damages?
3. If the supplier delivers materials to a construction site, and the site is not ready yet, so the supplier has to bring the materials back, who is responsible?

L. IT/internet

1. Do you use internet on your sites?
2. What use do you make of the internet to communicate with your supply chains?

M. Main Problem

1. What are the main problems associated with materials supply to a construction site.
2. What are the main problems associated with subcontractors works on construction site.
3. Is there any other important issue we should be concerned with?

N. Degree of Involvement

1. Do you have any shareholding in any of your subcontractors/suppliers?

Appendix A2
List of Questions for Subcontractor

Aims : to identify and supply chain management practice and its impact on site performance

The general questions below include;

A. Your company's characteristics
B. Obtaining work
C. Your suppliers
D. Site Performance
E. Customer satisfaction
F. Performance assessment
G. Incentives from clients/subcontractors/for suppliers*
H. Disputes,
I. Partnering
J. Risk and Uncertainties
K. IT/internet
L. Main Problems
M. Degree of Involvement

For the projects operating from your company's office, please provide the following information:

A. Your company's characteristics

1. (Client's profile) What kind of companies are your clients?
2. (Size). How many staff in this company?
3. (Size). How many branches throughout the UK?
4. (Size). What was the volume of sales in the last year?
5. (Complexity). What kind of materials do you need from your suppliers*?
6. (Complexity). How many suppliers do you normally work with on one project?*
7. (Complexity) How many main contractors do you ever work with at the same time?
8. (Duration). How long normally is the duration of your works?
9. (Speciality) What kind of work are you specialised in?
10. Do you own all the plant you use?

B. Obtaining work

1. How do you obtain work?
2. How do your clients know about you?
3. What kind of agreements (contracts) are normally used with your clients/main contractors?
4. Do your clients/main contractors give you detailed documents before they employ you?
5. Do you ever cooperate with a third party or subcontract your job or part of it when you have many works to be done at the same time?

C. Your suppliers*

1. What is the mechanism for supplier selection?*
2. What is the main consideration in selecting suppliers? *
3. Which do you prefer, local or national suppliers? *
4. How do you know about the suppliers? *
5. What kind of agreements (contracts) are normally used with your suppliers?*
6. Do you give detailed specification to suppliers before you make an order?*

D. Site Performance

1. Do you establish an office on site where you work?
2. What system do you use to monitor the efficiency of your operation on site?
3. What is the impact of late materials delivery on your site performance and how often does it happen?*
4. Do you benchmark your site performance against other similar projects in your firm or other firms?
5. Are you ever behind the agreed schedule? What causes this?

E. Customer satisfaction

1. Do you measure your customer satisfaction?
2. How do you measure it?

F. Performance assessment

1. How do your clients/main contractors assess your performance?
2. How do you assess the performance of your suppliers?*

G. Incentives from clients/main contractors/ for suppliers*

1. Do your clients/main contractors use any incentive (reward system) to encourage good performance from you?
2. Do you have any incentive (reward system) to encourage good performance your suppliers?*

H. Disputes

1. Have you ever had disputes with client/main contractor or suppliers*?
2. In what areas do most disputes occur?
3. How do you resolve the disputes?

I. Partnering

1. Do you build long term relationships with preferred client/main contractors/suppliers*?
2. What advantages are there for long term relationships?
3. Do you treat firms with whom you have long time relationships differently? (For example, by giving them special price or services?)
4. Of your clients, what percentage are one-off and what percentage are regular repeat business?

J. Risk and Uncertainties

1. If you are ready to work on site, and the site is not ready yet, so you have to delay your job, who is responsible?
2. If the material delivery from the supplier is late, so that the work on site is delayed, who is responsible?*
3. Is there any penalty in the contract for suppliers for late delivery? Do you pursue damages?*

K. IT/internet

1. Do you use internet on your sites? *
2. What use do you make of the internet to communicate with your supply chains? *

L. Main Problem

1. What are the main problems associated with your materials supply?*
2. What are the main problems associated with a subcontractor's works on construction sites.
3. Is there any other important issue we should be concerned with?

M. Degree of Involvement

1. Do you have any shareholding in any of your suppliers?*

Appendix A3
List of Questions for Material Suppliers

This preliminary survey aims at identifying supply chain management practice and its impact on site performance

The general questions below include;

A. Supplier's characteristics
B. Contract
C. Performance
D. Customer satisfaction
E. Competitive advantage
F. Technical operation
G. Flexibility and responsiveness
H. Disputes
I. Partnering
J. Risk and Uncertainties
K. Purchase order
L. IT/internet
M. Main problem
N. Consumer's behaviour

A. Supplier's characteristics

1. (Size). How many staff in this company?
2. (Size) How many branches throughout the UK?
3. (Size) What was the volume of sales in the last year?
4. (Maturity) When was the firm established?
5. (Speciality) What range of material do you supply?
6. (Complexity) How many projects can you supply at the same time?

B. Contract

1. What kind of agreements (contracts) are normally used with contractors/sub contractors?
2. Do contractors give you the detailed material specification before they make an order?

C. Performance

1. What system do you use to monitor the efficiency of your operation?
2. What parameters do you use to measure your own performance?
3. Do you benchmark your company's performance against other suppliers or against other industries?

D. Customer satisfaction

1. Do you measure your customer satisfaction?
2. How do you measure it?

E. Competitive advantage

1. What is the main concern of the contractor/sub contractor buying materials from your company? Is it price, quality, service or something else?

F. Technical operation

1. Do you ever deliver to a construction site which has such limited space for materials that you must deliver the materials on a JIT basis?
2. What percentage of your deliveries are late?
3. Who is responsible for unloading the materials from the truck to the storage area on site, the contractor or you?
4. Do you ever face difficulties in materials approval by contractors? In your opinion, what is the main reason for this?
5. If the materials you deliver are not approved, what will you do with those materials?
6. How often do you check your inventory?
7. Would it be helpful if you were involved in the design stage of major contracts?

G. Flexibility and responsiveness

1. Do contractors/subcontractors often make last-minute changes to delivery schedule, material specification (quality) or quantity?
2. How do you deal with those changes?
3. If you have an order of materials that you actually do not supply, are you going to say "no" or try to get the materials from other sources?

4. When you have a massive order, do you normally do outsourcing from other suppliers?
5. What is the average time for processing an order from a customer?
6. How do you forecast materials demand from your customers?

H. Disputes

1. Have you ever had disputes with contractors/subcontractors?
2. In what areas do most dispute occur?
3. How do you resolve the disputes?

I. Partnering

1. Do you build long term relationships with certain contractors?
2. What are the advantages of such long term relationships?
3. Do you treat firms with which you have a long term relationship differently; For example, by giving special prices or service, etc.
4. Which do you prefer, the one-off relationship or long term relationships? Why?
5. What is the percentage of the number of firms you deal with which you have long time relationships?

J. Risk and Uncertainties

1. Which of the materials you supply have the most uncertain customer demand? How do you deal with the stock for such materials?
2. If you deliver materials to a construction site, and the site is not ready so that you have to bring the materials back, who is responsible for this? Do you pursue damages?

K. Purchase order

1. How do you get an order from the contractor? Do you bid for it, or does the contractor select you without competition?
2. How do the contractors know about you? Is it because you advertise your company or because of the long time relationship?

L. IT/internet

1. Do you use the internet (website) to advertise your firm?
2. Do you use IT to coordinate with your branches throughout the UK?
3. Do you use IT to coordinate with your customers?

M. Main problem

1. What are your main problems associated with supplying materials to a construction site.
2. Is there any other important issue we should be concerned with?

N. Consumer's behaviour (judgement on decision making)

1. According to your experience, what is the most important thing that influences the customer's decision to buy from you?

Appendix A4

Summary of the interviews with contractors, subcontractor and supplier in the UK (preliminary investigation)

		'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
A	Project size	£100 K – 10 M , typical contract : £1.5-2M, Total budget for office £20M purely in CE	Small works upto 150k Other works £1m-25m Prefer job > £1m	Total sales in 2003: £25 million 350 total employees	Coxhoe quary 850,000 tonnes	-
B	Project complexity No of subcontractors/suppliers involved in a project	10 subcontractors, 10-15 suppliers	20-30 subcontractors the number of suppliers may vary from project to project.	Clients: main contractors; local authorities 2-3 suppliers 150 live contract with client	30-40 project sites	Generally CE has less subcontractor/suppliers than building works.-
C	Project Duration	4-6 months	Small works 6-12 months Others 17 weeks – 2 years Average 40-50 weeks	2 days - 6 months	-	CE work has less duration than building projects
D	Type of projects	2/3 roads & bridges, the rest is combination of marine	All/any (e.g. nursing homes, Ind office, schools, sports centres, city academic, hotels), except major civil (e.g. road, water, bridge, etc)	Earthworks But also has other divisions such as demolition, recycling, quarry, skip hire	Primarily dolomite limestone to the construction industry, 26 different products, civil construction, road, housing market, agricultural market, chemical market, block manufacturing	-
E	Obtaining work (how to get an order)			Mostly competitive tender (99%), negotiation (1%)	Always competition/competitive bid.	Most works are obtained by competitive tender. It shows the hard competition in civil construction industry.
F	How do clients know you?			Reputation for 60 years, website, brochure, advertisement in newspaper, TV,	Everybody knows.	-

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
					contract journal, PR company		
G	Subcontractor / Suppliers selection	Mechanism	'A' uses approved database, where to get into the database the contractor/suppliers must satisfy a number of criteria: financial, H&S, quality, environmental, management, experience	Competitive tender - 2 stage tender (but not always) 'B' has a lot of partnering jobs (negotiated works, D&B work)	Competitive tender (but not formal e.g. 2 envelope), negotiation.		Mechanism : competitive tender, negotiation.
		Main consideration	financial, H&S, quality, environmental, management, experience	Mainly Price, but also consider spec, program, availability of labour& materials, time zone	Price → for material suppliers Health and safety program → for subcontractor		Price is very important, but not the only one to be considered.
		Local/National	Prefer Local : because of competitiveness and nearby location Certain material goes for National framework : to get better price (discount)	Prefer local mainly due to competitive price, but may need to use national. (especially for specialized subcontractors/suppliers	Local, it is a company policy to develop north east economic (to keep money in North East region)		Generally, local suppliers/subcontractors are preferred due to the reason of competitiveness, nearby location, to keep money in the local area.,
		How do you know them?	'A' has been here for 30-40 years. Everybody knows anybody else. There is a clique.	Previous knowledge, internal database	From the internet, they sent their profile to 'C'		Since they are the old player in business, they know one another.
H	Contract	Kind of contract	Subcontractor → Back to back with our contract but with A's own condition. 'A' has its own subcontract from.	Subcontract order referring to main contract conditions 'B' has construction standard form.	Demolition division virtually always lump sum (NFDC contract) Earthworks usually remeasure, could be monthly payment	The materials will be predominantly from contract to contract, not project to project.	All tend to use their own standard contract form to suit their need.

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
			For supplier is just a contract order/purchase order.				
		Detail Specification from client before making order	(Spec & drawing from the client.)	(Spec & drawing from the client.)	Depends on the contract, some may send 2 pages, some may send a package	Yes	-
		Detail Specification for subcontractor/supplier before making order	Yes. By giving copy of BOQ and specification to suppliers	Yes.	yes		All give t the specification for the order.
		Subcontracting a job or part of the job (outsourcing)	(as a main contractor, subcontracting a certain part of job is common for sure).	(as a main contractor, subcontracting a certain part of job is common for sure).	Rarely subcontract a work, occasionally sub let a bit.	Yes if 'D' has to, but will try not outsource, but don't let the customer down.	Subcontractor and supplier try not to subcontract unless they have to.
I	Site Performance	Monitoring efficiency on site	'A' measure the performance (time) on weekly basis, cost is assessed monthly.	Regular on-site review meeting. Monthly report to Board of directors. Quality Assurance.	Work to a programme → weekly site meetings Monitoring time and quality.	turn round times(max 15 minutes	Contractor, subcontractor, supplier have their own monitoring system to monitor their efficiency on site.
		Late delivery of suppliers/subcontractors	Not unusual – commonly happen, frequently.	Not very often.	Not often, but can be a major impact (e.g. geotextile was 1.5 weeks late, bough some after 3 days, trying to recover cost from original supplier)		Late delivery of supplier/subcontractors happens but not very often. It may cause huge impact.
		(Benchmarking) internally	Yes. Series of 9 KPI to compare projects, not other firms. 'A' benchmark himself to KPI published by constructing excellent. (a government funded organization).	Yes. Internal comparison	Yes. There are standards, 'C' compare against them.		Benchmarking internally is preferred rather than externally, since external benchmarking is more difficult and need similar parameter which may not suit all companies.

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
		(Benchmarking) Externally	No. 'A' is not using the standard KPI since it is not always relevant to him.	No. it's very difficult and not really necessary.	No.	It is hard to do that. QPA provide a benchmark for the industry, `published market share,	
		Site Performance Parameter	1. Client satisfaction of product 2. Client satisfaction of service 3. Defects 4. Safety AFR 5. Predictability – Margin 6. Predictability – time 7. Staff turnover 8. Un-insured losses 9. Outstanding retentions	Time, cost, quality, Health & Safety, Resources availability (labour, material/plants)	Time Quality Quantity	KPI's → turn round times. (for customer service).	Each has different set of parameter to asses their site performance due to different need and characteristic of each company. (contractor, subcontractor, supplier)
J	Customers satisfaction	Do you measure it?	Yes	Yes	Not at present, but are thinking about it. The customers tell when 'C' is going wrong.	Yes	All are aware of the importance of achieving customer satisfaction.
		How?	KPI. By asking them through questionnaire.	Managing director visit clients and ask them to complete a questionnaire on 'B' performance and to suggest where improvement could be made.	-	Distribution team leader contacts sites personally if possibility of under -supply.	
K	Technical operation	Buy material as need it or in full quantity and set the delivery schedule?	Always do for the whole contract. 'A' gives indication of when to deliver.	Yes, bulk orders with delivery schedules.			Bulk orders and set the delivery schedules are more common, rather than buy material as needed.

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
		Buy and stockpile materials off-site to use them on-site at a later stage?	No. Avoid double handling.	No.			No stockpiling.
		Checking the materials/works of subcontractors thoroughly?	Yes, test material, check workmanship as required by 'A's Quality Assurance system, but still things do go wrong	Yes, though it is difficult to do this. (e.g. prepacked materials		'D' has lab unit to check the quality of aggregate he provide.	Material and subcontractor's work checking is a must to meet the specification.
		Responsibility for unloading the materials on site	Depend on the materials. Generally 'A' is responsible for unloading the materials, except for a big item, e.g. railway track which it is mentioned in sub contract/supplier order.	Depend on the quotation.		'D'	The responsibility for unloading the materials on site may very, depending on the type of material and quotation.
		Material disapproval due to specification.	Yes, 'A' rejects the materials mainly it happens for the raw materials (aggregate, surfacing) rather than manufactured goods. Quite rare to send back manufactured products like bricks, piles, pipes, since they are tend to be OK.	Yes. Normally happens for natural products, timber and damaged materials.		Yes (by the client), they want more coarse or more fine etc	Material disapproval does happen, especially for natural/raw products, not manufactured ones.
		Material delivery on JIT basis due to limited space on site				A lot of the time, tight sites, tight corners, need to key in to schedule The material should be tipped in where the materials will be rolled.	JIT delivery should be encouraged more since it can reduce time and cost, unnecessary stock, warehouse, resources, etc.
		Inventory checking				Stockpile visually Calculate quantity 6 month volume survey	-

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
						x density = tonnage.	
L	Performance assessment	Client over contractor/subcontractor			Main contractors review Thompson performance internally. Sites phone us to tell us any problems.	National questionnaire survey	Performance assessment can be done from top-down (Client-contractor/subcontractor/supplier) or bottom up (supplier-contractor/subcontractor). The feedback will be very important to do continuous improvement.
		Contractor to subcontractor/ supplier	'A' assesses the subcontractors every 6 months, by scoring 0-3. Subcontractor/suppliers asses 'A' at the end of each contract.	Meetings , end contract review	Sending questioner for suppliers and subcontractor.		
M	Incentives for subcontractors/suppliers	Incentive/reward system to encourage good performance from subcontractors/ suppliers	'A' are rewarded for savings. 'A' haven't started a rewards system related to Suppliers/subcontractors performance.	Normally it happens between client-contractor (50-50 or 40-60), not likely to be passed down supply chain	No. The clients may just give another job if they are satisfied. No. Just give another job (repeat business)		The incentives scheme is not really working along the supply chain, i.e. not passed down along the supply chain. There is a gap between theory and practice. There is a gap between theory and practice.
N	Disputes	Disputes with subcontractors/ suppliers	Common happens.	yes	Not many. 3 major claims within 22 years (with client)	Yes	Common area of disputes: quality (material & workmanship), financial
		In what area	Poor performance, quality of workmanship	Material (e.g. timber. Concrete), non performance of workmanship, financial (disagreement of price, additional cost due to exceptional adverse weather, cost work acceleration due to late delivery/completion)	Money/payment	Payment, quality, delivery, contract status, credit status → 'D' tries to control and reduce the disputes.	

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
		Resolution for disputes	Always resolve, but there maybe recompensate from subcontractors/suppliers. Can't recall going to court with a subcontractor/suppliers. The worst one 'A' tries to go for an arbitration rather than a court.	Meetings, negotiation, sometime adjudication. (no court, since it will be very costly) Negotiation with no blame scenario, no prejudice (move forward to solve ..... & avoid problem by being proactive) Satellite workshops	Negotiation. It would take a lot to go to court, so that it should be avoided	Take an individual case/specific case, negotiation → tailored to each disputes No court case.	Generally, resolution for dispute is: negotiation. Rare to go for adjudication, arbitration or even court, since it'll be costly and take times so long.
O	Partnering	Building long term relationships	Yes, particularly in last 3 years, generally lead by enlightened clients (Highway Agency).	Yes. No	Yes. (e.g. city of Sunderland for demolition jobs of lots of homes over 5 years, Durham city council – target cost after pricing a BOQ – cost reimbursement+ contract)	Yes, want to be supplier of first choice for a lot of different companies	All are interested in doing partnering due to the advantages such as closer relationships, early stage involvement, having special price, etc. Although the contractors see partnership as an important one, they still need to check the market price of products or services offered by their subcontractors and suppliers.
		Advantages of long term relationships	'A' has input at early stage by the involvement of suppliers, which they may suggest alternative materials	Can become complacent but is still the way forward Favourable rates/relations.	Involvement at design stage so that can suggest best alternative to minimize the cost, save client's money, save time.	Planning volumes/sales. → very stable budget.	
		Treat long term partners differently?	Yes. Key supplier like tarmac is involved in the tender stage which give him added value, but still go out to tender.	Yes	Yes, rarely. If they were offered.	Would give partners good service where possible, but not to disadvantage one-off customers.	
		% one-off type supplies or regular repeat business	Subcontractors → 75% regular repeat business Supplier → 75% regular	90-95% repeat business	75% regular, 25% one-off	Maybe around 5% long term relationship→ small percentage but	

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
			repeat business			*high volume*	
P	Risk and Uncertainties	Percentage of late delivery	Not often	Not often	Not often	N/A. Majority of customer state A.M. delivery	Late delivery does not often happen.
		Responsibility for late delivery which cause work on site is delayed	The supplier is responsible.	The supplier	The supplier		The responsibility of late material delivery mainly lies on supplier, assuming that sufficient notice was given.
		Penalty for late deliveries. Pursue damages?	Probably not, only for large organisation. They can stand against the additional charge, but it is not the case for small company.	Not as vigorously as he should	Usually no.		Unless it costs too much, and related to big organisation, pursuing damages is not likely to be done.
		The site is not ready yet for material sent by suppliers or work to be done by subcontractor, who is responsible?	The main contractor and he will be charged by suppliers.	The contractor, but no charge from the supplier due to good relationship between them.	Client (main contractor) , but it does not happen, if incurred a lot of cost will approach the client. Hassle not recharged.	Rarely happens – predominantly the customer tells when they want the material to be delivered as the site is ready. try to find a way to use it else where, otherwise bring it back to stock it or be recycled.	It is the responsibility of contractor to prepare site so that material can be delivered and subcontractor's work can be done.
Q	IT	Internet use on site	Generally, sites have access to the internet. Not use for anything. Have a company intranet. H&S and project plan come off the internet.	No, very rare. Limited benefit on site. Some site managers have laptop	No (considering security problem on site), main contractor does.	No	The internet use on site is still limited.
		What use do you make of internet to	Not used at the moment. Most emails are internal in the	No, Only use phone, fax,	Yes, to communicate with	Computer link- Account system direct link with	Some has made use of the internet to communicate with

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
		communicate with your supply chains.	company. Project extranet to see where we are in the program	meeting	subcontractor/suppliers. To look for materials (only had it 6-9 months)	regular (key) customer. Internet site with specific customer.	supply chain, some others have not.
R	Main problem	Main problems associated with materials supply on site	-	delivery	No major problem, can get all we want. Suppliers are ahead of the game- can ask his advice, they may advise to use certain kind of materials.	When the machine breaks down, the customer service will be affected.	Delivery, fast response and communication are the main concern in the supply chain.
		Main problem associated with subcontractors works on sites	-	Lack of labour and keeping up to a programme Price and availability Adherence to programme	Not enough time to react. Need fast response.		
		Any other important issues?	-	Communication of intentions	Time is a very important issue. Fast response is vital.		
S	Degree of involvement	Involvement in early stage of contract	Yes	yes	Yes. It may reduce time and cost.	Major contract → involved. Customer liaise (major customer) with 'D', coming to site so that they can see if 'D's' materials can suit the contract.	Involvement of contractor/ subcontractor and supplier in early stages of the contract may contribute many alternative ideas, and in turn may reduce cost and time.
		Shareholding in any of subcontractors/suppliers.	'A' bought some companies and they are now specialist division: Soil mechanics, materials testing, piling Different part of the industry are likely to have different approaches	No	-		-

Appendix A4 (Continued)

			'A' (CE Division)	'B' (Building contractor)	'C' (Subcontractor)	'D' (Supplier)	Comments
T	Flexibility and responsiveness	last-minute changes to delivery schedule, material specification (quality) or quantity?				Yes, very often. Quality issues.	The idea of being flexible and responsive to customer demand is very important in order to achieve customer satisfaction.
		How do you deal with those changes				Responsive, good communication.	
		If you have an order of materials that you actually do not supply, are you going to say "no" or try to get the materials from other sources?				Never say no, but does not say yes straightaway. Look for the next best plan, recommend other product.	
		average time for processing an order from a customer				Do they have an account? Red or black, weigh bridges has computer print out 4-5 minutes.	
		forecast materials demand from your customers				Building customer relationships + commercial dept. From the past projects they have done previously with customers, so 'D' may notice the kind of material, the quality and the quantity the customers want.	

Appendix A5
Identification of delay factors

Identification of causes of delays and cost overruns by Koushki *et al* (2005)

1. Variation orders
2. Owner's financial constraints
3. Owner's lack of experience
4. Materials
5. Weather
6. Labour
7. Contractor

Identification of delays and cost overruns by Frimpong and Oluwoye (2003)

1. Project financing factors
    - Monthly payment difficulties
    - Contractors, financial difficulties
    - Fraudulent practice
2. Natural conditions factors
    - Bad weather and unexpected natural events
    - Unexpected subsoil and ground conditions
    - Environmental concerns
3. Materials factors
    - Procurement problems
    - Imported materials
    - Late delivery
    - Difficulties in obtaining materials at official prices
4. Labour factors
    - Shortages
    - Low skill levels
    - Industrial relations labour and management relation
5. Plant/Equipment factors
    - Frequent breakdowns
    - Shortages
    - Transportation problems
    - Low efficiency
6. Projects planning and controlling related factor causes of overruns
    - Deficiencies in planning, scheduling and cost estimates prepared
    - Insufficient project manager authority and influence
    - Communication among the various parties
    - Inadequate control procedures
7. Economic factors
    - Fluctuations in material and plant/equipment costs
    - Inflation
8. External factors
    - Social events
    - Governments policies and politics
    - Restrictions
    - Delays in inspection and testing of completed work
9. Contractual relationship factors
    - Poor contract management
    - Low bid
    - Slow decision-making
    - Claims/disputes
    - Contract negotiation
    - Insurance problems

Identification delay factors by Manavazhia, and Adhikarib (2002)

1. Organizational weakness (contractors)
    - High turnover of staffs which result in the loss of continuity and consequent breakdowns in the command structure and communications.
    - Minimum number of qualified staffs
    - An absence of systematic record-keeping and Lack of preplanning
    - Poor understanding of contract clauses and documents
2. Supplier default
    - Monopoly control of the market by some suppliers,
    - Work stoppages in factories manufacturing materials,
    - Fluctuating demands forcing suppliers to wait for accumulation of orders
    - Difficulties in importing required raw materials from other countries.
3. Governmental regulations
    - Delays in sanctioning the release of foreign currency required for importing materials and equipment,
    - Delays in customs clearance,
    - Bureaucratic procedures
    - Red tape.
4. Transportation delays
    - Landslides
    - Heavy rainfall.
    - Intense cold

Identification of delay factors by Al-Momani (2000)

1. Poor design,
2. Change orders,
3. Weather,
4. Site conditions,
5. Late delivery,
6. Economic conditions
7. Increase in quantity

Identification of delay factors by Chan and Kumaraswamy (1997)

1. Project-related factors include causes of delays related to:
    - project characteristics,
    - necessary variations,
    - communication among the various parties,
    - speed of decision making involving all project teams,
    - ground conditions.
2. Client-related factors include those concerned with:
    - client characteristics,
    - project financing,
    - their variations and requirements,
    - interim payments to contractors.
3. Design team-related factors consist of:
    - design team experience,
    - project design complexity,
    - mistakes and delays in (producing) design documents.
4. Contractor-related factors comprise those related to:
    - contractor experience in planning and controlling the projects
    - site management and supervision,
    - degree of subcontracting,
    - their cash-flow.
5. Materials factors include causes related to:
    - shortages,
    - materials changes,

- procurement programming,
- proportion of off-site prefabrication.

6. Labour factors encompass:
   - labour shortages,
   - low skill levels,
   - weak motivation,
   - low productivity.
7. Plant/Equipment factors include:
   - shortages,
   - low efficiency,
   - breakdowns, and
   - wrong selection.
8. External factors comprise those such as:
   - waiting time for approval of drawings and test
   - samples of materials, and
   - environmental concerns and restrictions.

Identification of delay factors by Kaming et al (1997)

1. Unpredictable weather conditions
2. Inaccuracy of materials estimate
3. Inaccurate prediction of craftsmen production rate
4. Inaccurate prediction of equipment production rate
5. Material shortage
6. Equipment shortage
7. Skilled labour shortage
8. Locational restriction of the project
9. Inadequate planning
10. Poor labour productivity
11. Design changes

Identification of sources and delays by Ogunlana and Promkuntong (1996).

1. Owners
   - Change orders
   - Slow decision-making
2. Designers
   - Incomplete drawings
   - Slow response
3. CM or Inspector
   - Deficiencies in organisation
   - Deficiencies in coordination
   - Uncompromising attitude
   - Delays in work approval
4. Contractors
   - Materials management problems
   - Deficiencies in organisation
   - Coordination deficiencies
   - Planning and scheduling problems
   - Equipment allocation problems
   - Financial difficulties
   - Inadequacy of site inspection
5. Resources
   - Shortage of construction materials suppliers
   - Late delivery
   - Price escalation
   - Low quality of materials
   - Shortage of site workers
   - Shortage of technical personnel

- Insufficient numbers of equipment
- Frequent equipment breakdown

6. Others
   - Confined site
   - Problems with neighbours
   - Slow permits by Government agencies

Identification of delay factors by Assaf and Al-khalil (1995)

1. Materials
   - Shortages
   - Change in types and specifications during construction
   - Slow delivery
   - Damage in storage while needed on site
   - Delay in the special manufacture out of country
2. Manpower
   - Shortage
   - Labour skill
   - Nationality of labourer
3. Equipment
   - Failure
   - Shortage
   - Unskilled operators
   - Slow delivery
   - Poor productivity
4. Financing
   - By contractor during construction
   - Delays in contractors' progress payments by owner
   - Cash problems during construction
5. Changes
   - Design changes by owner or agent during construction
   - Design errors made by the designers
   - Foundation conditions encountered in the field
   - Mistakes in soil investigation
   - Water table condition on site
   - Geological problems on site
   - Errors committed during field construction on site
6. Government relations
   - Obtaining permits from municipality
   - Obtaining permits for labourers
   - Excessive bureaucracy in project-owner operation
   - Building code used in design of projects
7. Scheduling and controlling
   - Preparation and approval of shop drawings
   - Waiting for sample materials approval
   - Preparation of scheduling networks and revisions by consultant while construction is in progress
   - Lack of training personnel and management support to model the construction operation
   - Lack of database in estimating activity duration and resources
   - Inadequate early planning of the project
   - Accident during construction
8. Environment
   - Hot weather effect on construction activities
   - Rain effect on construction activities
   - Insufficient available utilities on site
   - Social and cultural factors
9. Contractual relationship
   - Relationship between different subcontractors' schedules in execution of project

- Conflict between contractor and consultant
- Difficulty of coordination between various parties (contractor, subcontractor, owner, consultant) working on project
- Insufficient communication between the owner and designer in the design phase
- Unavailability of professional construction management
- Controlling subcontractors by general contractors in execution of work
- Unavailability of financial incentive for contractor to finish ahead of schedule
- Negotiations and obtaining of contracts
- Legal disputes between various parties in the construction project
- Project delivery system used (PCM, design-build, general contracting, turnkey, etc.)

Identification of delay factors by Hensey (1993)

1. Materials
2. Labour
3. Equipment
4. Financial factors.
5. Improper planning
6. Lack of control
7. Subcontractor delays
8. Poor co-ordination
9. Inadequate supervision
10. Improper construction methods
11. Technical personnel shortages
12. Poor communication.

Identification of delay factors by Al-Hammad (1993)

1. Delay in contract progress payment
2. Lack of construction quality
3. Errors and delays in shop drawings, and approval of sample materials
4. Legal disputes
5. Scheduling
6. Conflicts among subcontractors
7. Geological problems
8. Weather conditions.

Appendix A6
The process of selecting the delays related to SCM, defining the impact and the operationalability

Delays		SCM related?	Time of occurrence		Direct impact on site activity		Can it be operationalised ?
			pre project's start	during construction	Start date	Duration	
Material related	late delivery	Y	-	Y	Y	Y	Y
	wrong specs	Y	-	Y	Y	Y	Y
	wrong quantity	Y	-	Y	Y	Y	Y
	poor quality	Y	-	Y	-	Y	Y
	Difficulties in obtaining materials	Y	-	Y	Y	Y	Y
	shortages of materials on site	Y	-	Y	Y	Y	Y
	damage materials on arrival	Y	-	Y	Y	Y	Y
	Shortage of materials in markets	Y	-	Y	Y	Y	Y
	poor material planning	Y	Y	-	Y	Y	-
	poor monitoring & control	Y	Y	-	Y	Y	-
	proportion of off-site prefabrication.	Y	Y	-	Y	Y	-
Financial related	owner's financial constraints	-					
	project financing	-					
Labour	Shortage of skilled labour	Y	-	Y	Y	Y	Y
	Foremen shortages	Y	-	Y	Y	Y	Y
	Senior staff shortages	Y	-	Y	Y	Y	Y
Client related	financial constraints	-					
	variation / changing order	-					
	slow decision making	-					
	Unrealistic contract durations imposed by client	-					
	Long waiting time for approval of test samples of materials	Y	-	Y	Y	Y	Y
CM or inspector	Deficiencies in coordination	Y	Y	Y	Y	Y	Y
	Delays in work approval	Y	-	Y	Y	Y	Y
Designer	design error	-					
	Delays in design information	Y	Y	-	Y	Y	Y
	Mistakes and discrepancies in design documents	-					
	incomplete drawing	-					
	slow response	Y	Y	-	Y	Y	Y
Main contractor	material management problems	Y	-	Y	Y	Y	-
	planning and scheduling problems	Y	-	Y	Y	Y	-
	equipment management problems	Y	-	Y	Y	Y	-
	shortage of manpower.	Y	-	Y	Y	Y	Y
	Improper control over site resource allocation	Y	-	Y	Y	Y	-
Subcontractor	unreliable subcontractor	Y	-	Y	Y	Y	-
	interference with other trade	Y	-	Y	Y	Y	Y
	slow mobilisation	Y	-	Y	Y	Y	Y
	Delays in subcontractors' work	Y	-	Y	Y	Y	Y
Supplier related	monopoly control of the market by some suppliers	Y	-	Y	-	-	-

Appendix A6 (Continued)

Delays		SCM related?	Time of occurrence		Direct impact on site activity		Can it be operationalised ?
			pre project's start	during construction	Start date	Duration	
	work stoppages in factories manufacturing materials	Y	-	Y	-	-	-
	fluctuating demands forcing suppliers to wait for accumulation of orders	Y	-	Y	Y	Y	-
	difficulties in importing required raw materials from other countries.	Y	-	Y	Y	Y	Y
Governmental regulation	policy on foreign currency required for importing materials and equipment	Y	Y	Y	-	-	-
Plant/Equipment factors include	Shortages of plants.	Y	-	Y	Y	Y	Y
Projects planning and controlling related factor causes of overruns include:	Deficiencies in planning, scheduling and cost estimates prepared.	Y	Y	-	Y	Y	-
	Lack of commitment to budget and schedule	Y	Y	-	Y	Y	-
	Lack of project team participation in setting schedules	Y	Y	-	Y	Y	-
	Communication among the various parties.	Y	Y	Y	Y	Y	-
	Waiting for information	Y	Y	Y	Y	Y	
Economic factors	Fluctuations in material and plant/equipment costs.	Y	-	Y	-	-	-
	Escalation of material prices	Y	-	Y	-	-	Y
	Difficulties in obtaining construction materials at official current prices	Y	-	Y	Y	Y	Y
External factors include:	Delays in inspection and testing of completed work.	-					
	Delays in work approval	-					
	Delays in construction permits	-					
Contractual relationship factors	Slow decision-making.	Y	Y	-	Y	Y	Y
Project related	project information (completeness)	Y	Y	-	Y	Y	Y
	Lack of communication between consultant & contractor	Y	Y	Y	Y	Y	-
	Low speed of decision making involving all project teams	Y	Y	Y	Y	Y	-
	Inappropriate overall organizational structure linking all project teams	Y	Y	-	Y	Y	-
	Long waiting time for approval of drawings	Y	Y	-	Y	Y	Y
	Lack of communication between client and consultant	Y	Y	Y	Y	Y	-
	Slow information flow between project team members	Y	Y	Y	Y	Y	-
	Deficiencies in planning and scheduling at preconstruction stage	Y	Y	-	Y	Y	-
	Shortage of plant/equipment	Y	Y	-	Y	Y	Y

Appendix A6 (Continued)

Delays		SCM related?	Time of occurrence		Direct impact on site activity		Can it be operationalised ?
			pre project's start	during construction	Start date	Duration	
	Small extent of design information available at construction start	Y	Y	-	Y	Y	Y

Appendix A7

Cover letter and questionnaire for the main survey

5 January 2006

Dear Sir/Madam,

"How supply chain management practice may impact on construction project performance"

I am a PhD student conducting research in the field of Construction Management under the supervision of Dr. Steve Scott in the School of Civil Engineering and Geosciences at Newcastle University. The research aims to investigate *how supply chain management practice may impact on construction project performance.*

Your company has been selected since you are one of top 150 contractors companies in the United Kingdom and are involved in building work.

The questions in the questionnaire refer to a typical school building project located in the United Kingdom and relate to delays caused to the project by the supply chain. It is expected that this questionnaire would be filled in by one of your employees who has experience as a **site manager** in building similar projects.

I would be very grateful if you would arrange to complete the attached questionnaire, and return it to me using the enclosed pre-paid envelope, preferably by the 25 January 2006.

Please note that your responses will be completely confidential, and all the information you provide will be used purely for the purposes of this research.

Thank you very much in advance for your assistance.

Yours faithfully,

Jati Hatmoko
School of Civil Engineering and Geosciences,
Postgraduate room 1st floor, Cassie Building
University of Newcastle upon Tyne, NE1 7RU
Email j.u.d.hatmoko@ncl.ac.uk phone 07817938661 Fax 0191- 222 6502

Questionnaire

The questions in this questionnaire refer to a typical school building project located in the United Kingdom as shown in figure 1 below and relate to delays caused to the project by the supply chain.

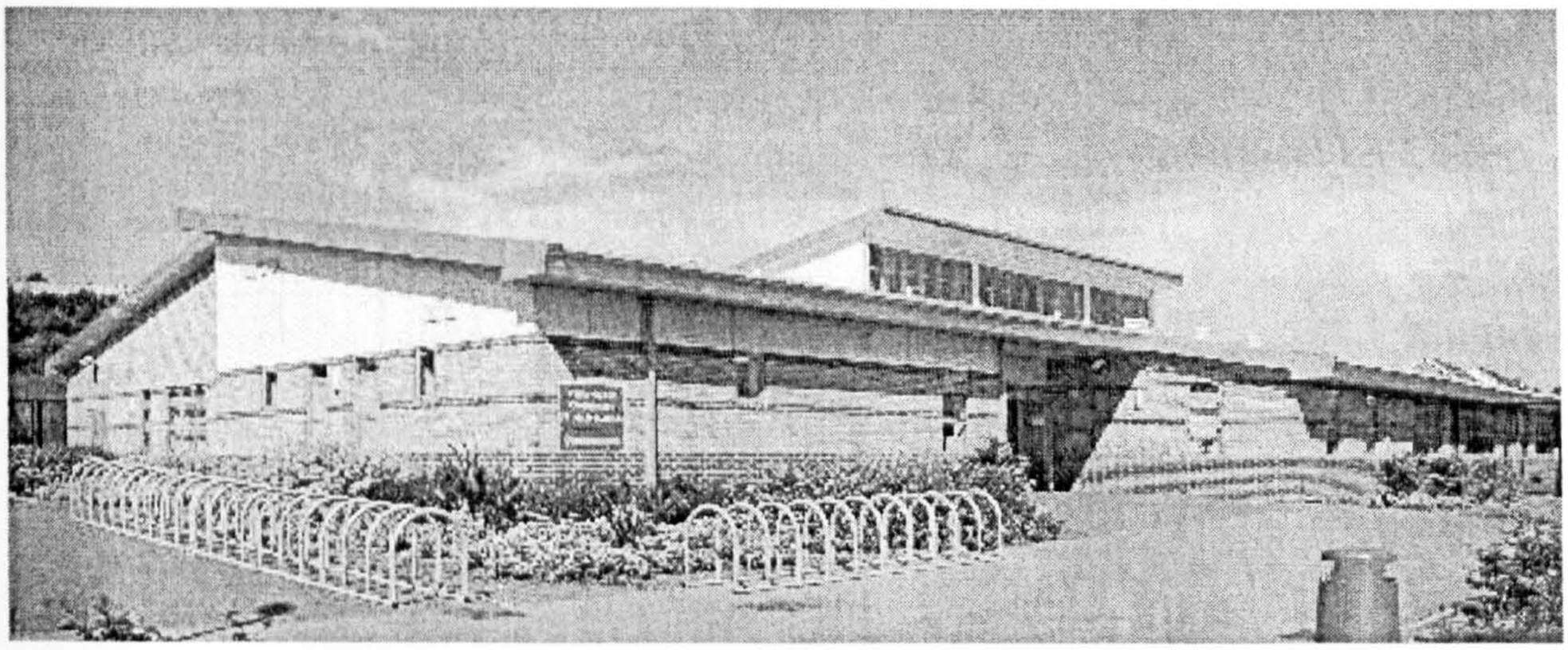


Figure 1. A typical school building in the United Kingdom

You may find the questions in this questionnaire quite difficult to answer, but please use your experience of building similar projects to give your best estimates.

Some of the questions ask you to estimate in percentage terms how often certain events may occur, for example, "How often would delivery of materials be later than the scheduled delivery date?". In this example, it then asks for information about the extent of the delays if it does occur and ask you to state the minimum delay, most likely and maximum delay as shown in figure 2.

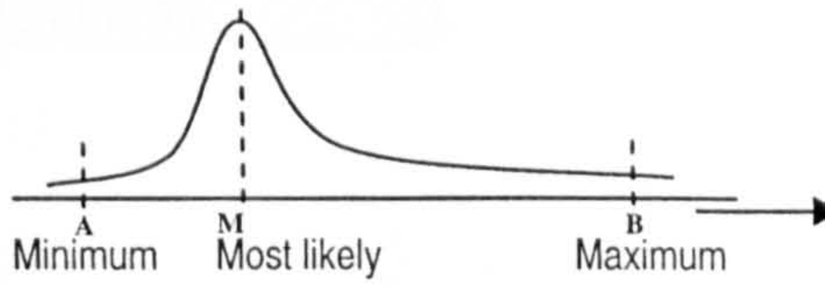


Figure 2. Extent of delays

Company details

Name of company : .....

Name of respondent : ..... Position :.....

Years of respondent's experience in the construction industry : .....

Subcontracting

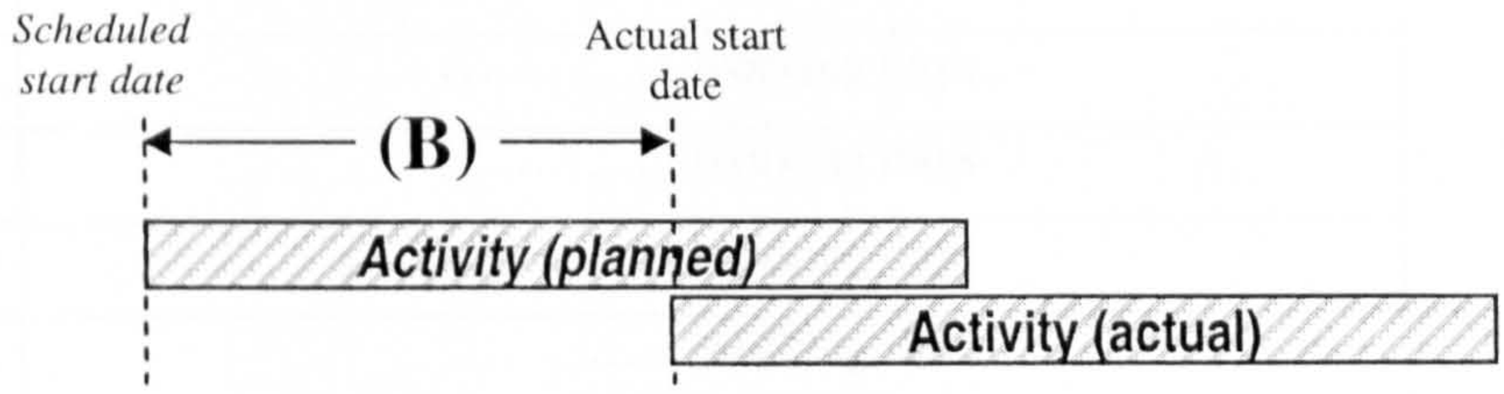
1 a. Please indicate for the typical school project shown, the **six main areas** of work that typically would be **subcontracted** to specialist subcontractors?

Work 1 : .....
Work 2 : .....
Work 3 : .....
Work 4 : .....
Work 5 : .....
Work 6 : .....

b. How often do you estimate that these subcontracted works would **start later than the scheduled date**? *Please indicate in percentage in column A below.*

	A
Work 1	..... %
Work 2	..... %
Work 3	..... %
Work 4	..... %
Work 5	..... %
Work 6	..... %

c. When these works do **start later than the scheduled date**, please estimate how late **(B)** they could be? *Please indicate the minimum, most likely and maximum in working days (column B)*



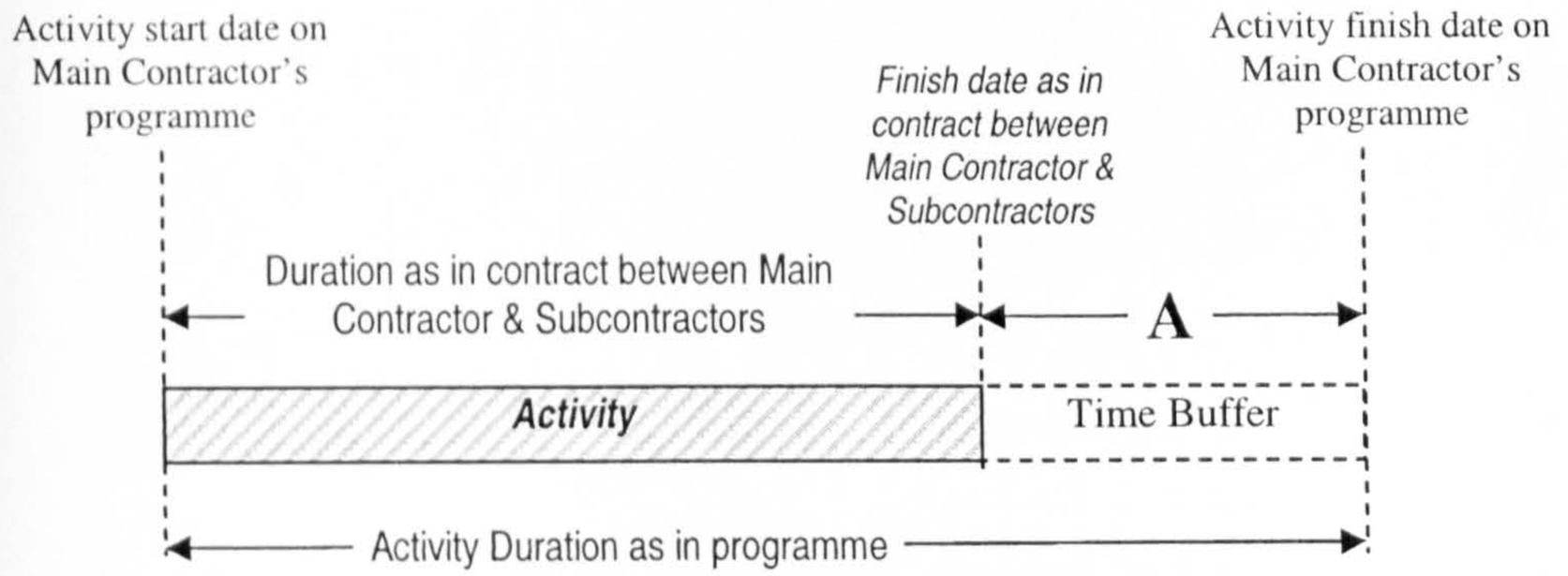
	B		
	Min (working days)	Most likely (working days)	Max (working days)
Work 1			
Work 2			
Work 3			
Work 4			
Work 5			
Work 6			

2 For subcontracted work, do you tend to set a **completion date earlier** than your programme requires, in case there are problems with the subcontractor's performance (a time buffer)? *(Please answer by ticking the boxes below)*

☐ Yes. *Please go to the question no. 3*

☐ No. *Please go to the question no. 4*

3 Referring to the subcontracted works you have mentioned in question no. 1a, please indicate the **time buffer** you would use with your subcontractors?* *(Please see the illustration below and indicate in column A)*



	A
	For the subcontracted works in question no. 1a, please indicate how long the time buffer would be
Work 1	…….. working days
Work 2	…….. working days
Work 3	…….. working days
Work 4	…….. working days
Work 5	…….. working days
Work 6	…….. working days

ALTHOUGH YOU MAY NORMALLY USE SUBCONTRACTORS FOR MUCH OF THE WORK OF SUCH PROJECTS, PLEASE ANSWER THE FOLLOWING QUESTIONS AS THOUGH YOU WERE CARRYING OUT ALL THE WORK OF THE PROJECT YOURSELF.

Material flows

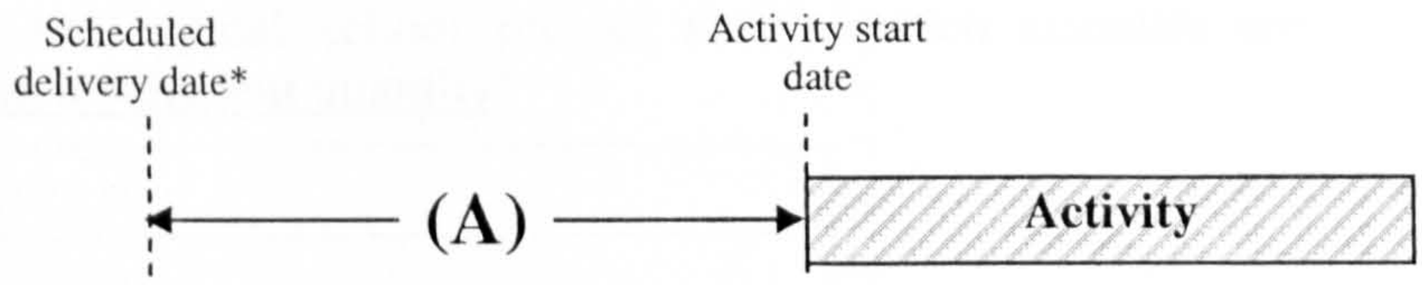
4 a. How often do you estimate that **delivery of the materials** below would be **later than the scheduled delivery date**? *Please indicate in percentage in column A below.*

b. When these **delays** do occur, please estimate their duration in working days, by specifying minimum, most likely and maximum. *Please indicate in column B below.*

Materials	A	B		
	How often do you estimate that delivery of the materials below would be later than the scheduled delivery date?	Extent of delay (in working days)		
		min	most likely	max
1. structural steelwork	…….. %			
2. steel reinforcement	…….. %			
3. precast concrete element	…….. %			
4. bricks	…….. %			

Materials	A	B		
	How often do you estimate that delivery of the materials below would be later than the scheduled delivery date?	Extent of delay (in working days)		
		min	most likely	max
5. windows & doors	..... %			
6. roofing materials	..... %			
Other (please specify) ☐	..... %			
☐	..... %			

5 Typically, **how many working days in advance (A)** of an activity do you schedule your delivery date for these materials? *Please indicate in column (A) below.*



*Note: Scheduled delivery date refers to the date when the materials are **expected** to be delivered on site (**NOT** the date when an order has been placed)

	(A) working days in advance
1. structural steelwork	..... working days
2. steel reinforcement	..... working days
3. floor tiles	..... working days
4. bricks	..... working days
5. windows & doors	..... working days
6. roofing materials	..... working days

6 a. Please indicate for the typical school project shown which materials are commonly **delivered with the wrong specifications**?

Material 1 : .....
Material 2 : .....
Material 3 : .....
Material 4 : .....

b. How often do you estimate that these materials would be **delivered with the wrong specifications**? *Please indicate in percentage in column **A** below.*

	A
Material 1	..... %
Material 2	..... %

Material 3	..... %
Material 4	..... %

c. How long does it take to get **replacement materials**? *(Please the minimum, most likely and maximum in column B below)*

	B		
	Min (working days)	Most likely (working days)	Max (working days)
Material 1			
Material 2			
Material 3			
Material 4			

7 a. Please indicate for the typical school project shown which materials are commonly **delivered in insufficient quantity**?

Material 1 : .....
Material 2 : .....
Material 3 : .....
Material 4 : .....

b. How often do you estimate that these materials would be **delivered in insufficient quantity**? *Please indicate in percentage in column **A** below.*

	A
Material 1	..... %
Material 2	..... %
Material 3	..... %
Material 4	..... %

c. What delay do you estimate this might cause to **the duration of an activity**? *(please the minimum, most likely and maximum and give a response for all materials in column B below)*

	B		
	Min (working days)	Most likely (working days)	Max (working days)
Material 1			
Material 2			
Material 3			
Material 4			

8 a. Please indicate for the typical school project shown which of the materials below are commonly delivered **damaged on arrival**? *(Please indicate by ticking the boxes below in column A).*

b. How often do you estimate that these materials would be **damaged on arrival**? *Please indicate in percentage in column **B** below.*

c. How long does it take to get a **replacement** for these damaged materials? *(Please indicate the minimum, most likely and maximum in column C)*

A	B	C		
Which of the materials below are commonly delivered **damaged on arrival**? *(Please indicate by ticking the boxes below)*	How often do you estimate that these materials would be **damaged on arrival**?	How long does it take to get **replacement** for these damaged materials? *(please indicate in working days the minimum, most likely and maximum)*		
		Min	Most likely	Max
Windows & doors	..... %			
Shower cubicles	..... %			
Ceiling	..... %			
Other (please specify)	..... %			
.....	..... %			
.....	..... %			

9 a. Please indicate for the typical school project shown which materials are likely to be **difficult to find in the market*** so that they may delay the start date of an activity?

**Note: Difficulties in obtaining materials in the market may be due to: scarcity in the market, problems with importing materials, problems with specially-designed materials, etc.*

Material 1 : .....
Material 2 : .....
Material 3 : .....
Material 4 : .....

b. How often do you estimate that you find difficulties in obtaining these materials in the market so that they may delay the start date of an activity? *Please indicate in percentage in column **A** below.*

	A
Material 1	..... %
Material 2	..... %
Material 3	..... %
Material 4	..... %

c. What **delay** do you estimate this might cause to the **start date of an activity**?
(please indicate_the minimum, most likely and maximum and give a response for all materials in column B below)

	B		
	Min (working days)	Most likely (working days)	Max (working days)
Material 1			
Material 2			
Material 3			
Material 4			

Labour and plant/equipment flows

10 a. Please indicate which type of **skills** might be **in shortage** during the construction phase of the typical school project shown. *Please indicate by ticking the boxes in column A below.*

b. **How often** do you estimate that the **shortage of this skilled labour** would occur? *Please indicate in column B below.*

c. What **delay** (in working days) do you estimate this might cause to **the duration of activities** where this skill is needed? *Please indicate the minimum, most likely and maximum in column C below.*

A	B	C		
Please indicate which **skills** might be **in shortage** on a construction phase of the typical school project shown	How often do you estimate that the **shortage of this skilled labour** would occur?	What delay (in working days) do you estimate this might cause **the duration of activities** where this skill is needed?		
		Min	Most likely	Max
Joiner	..... %			
Bricklayers	..... %			
Steel work erectors	..... %			
Labourer	..... %			
Concrete gang	..... %			
Plasterer	..... %			

A	B	C		
Please indicate which **skills** might be **in shortage** on a construction phase of the typical school project shown	How often do you estimate that the **shortage of this skilled labour** would occur?	What delay (in working days) do you estimate this might cause **the duration of activities** where this skill is needed?		
		Min	Most likely	Max
Scaffolders	..... %			
Plumbers	..... %			
Electrician	..... %			
Other (please specify)	..... %			
.....	..... %			

11 a. Please indicate for the typical school project shown which **plant** types or equipment or temporary works (e.g. scaffolding, falsework, formwork, etc) are likely to be in **shortage** during the construction phase?

Plant / equipment / temporary works 1 : .....
Plant / equipment / temporary works 2 : .....
Plant / equipment / temporary works 3 : .....
Plant / equipment / temporary works 4 : .....

b. How often do you estimate that this **shortage** would occur on the typical school project shown? *(Please indicate in percentage in column **A** below).*

	A
Plant / equipment / temporary works 1	..... %
Plant / equipment / temporary works 2	..... %
Plant / equipment / temporary works 3	..... %
Plant / equipment / temporary works 4	..... %

c. What **delay** do you estimate this might cause to the duration of activities where this plant, equipment or temporary works are needed? *(Please indicate in the minimum, most likely and maximum in column B below)*

	B		
	Min (working days)	Most likely (working days)	Max (working days)
Plant / equipment / temporary works 1			
Plant / equipment / temporary works 2			
Plant / equipment / temporary works 3			
Plant / equipment / temporary works 4			

Information flows

12 a. Please indicate for the typical school project shown what **activities on site** are likely to be affected by the fact that the main contractor has to **wait for a decision/ approval/ information/ instruction from the client/architect**?

Activity 1 : ……..……..
Activity 2 : ……..……..
Activity 3 : ……..……..
Activity 4 : ……..……..

b. How often do you estimate that the main contractor would have **to wait for a decision/approval/information/instruction** from the client/architect? *Please indicate in percentage in column A below.*

	A
Activity 1	……. %
Activity 2	……. %
Activity 3	……. %
Activity 4	……. %

c. What **delay** do you estimate this might cause to the **start date of an activity**?
Please indicate the minimum, most likely and maximum and give a response for all activities in column B below.

	B		
	Min (working days)	Most likely (working days)	Max (working days)
Activity 1			
Activity 2			
Activity 3			
Activity 4			

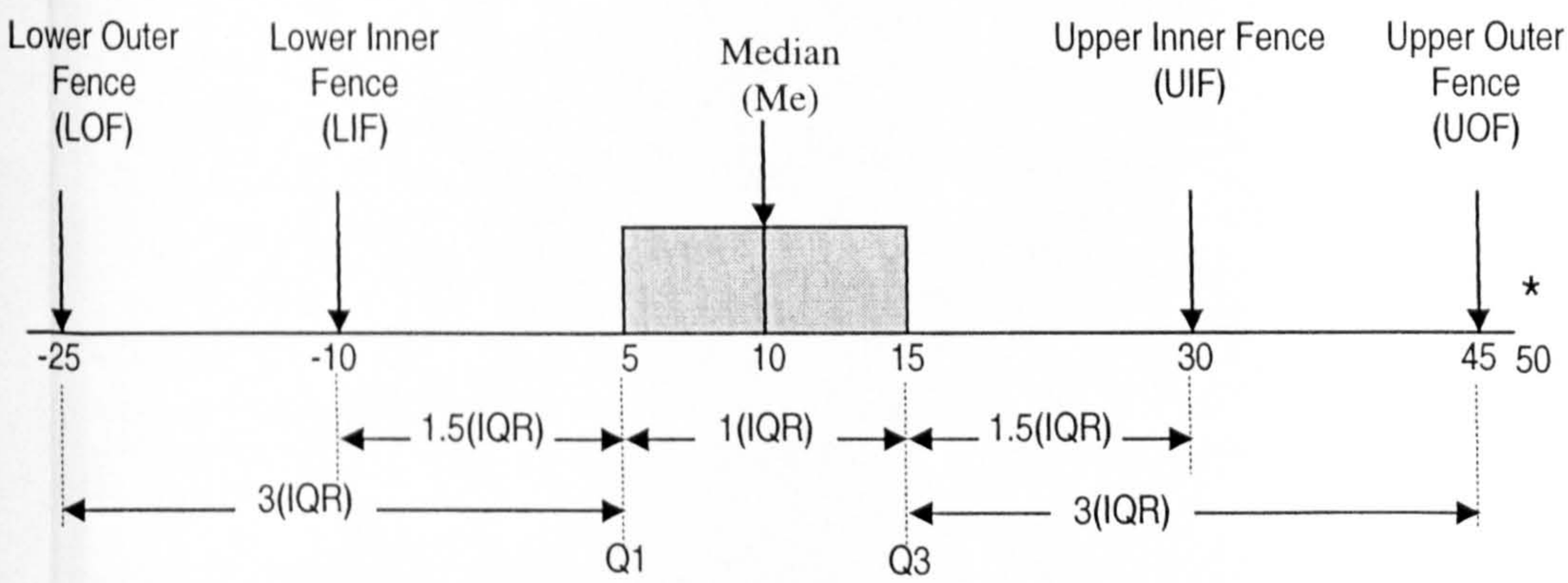
Your participation and co-operation in this survey has been most valuable. Please kindly put the questionnaire in the accompanying self-addressed envelope and mail it back to us.

Thank you

Jati Hatmoko
School of Civil Engineering and Geosciences,
Postgraduate room 1st floor, Cassie Building
University of Newastle upon Tyne NE1 7RU
Email j.u.d.hatmoko@ncl.ac.uk phone 07950458505 Fax 0191- 222 6502

Appendix A8
Detecting outliers with boxplot method

Outliers can be identified by constructing a box plot of the data. In this method, the median (Me), 1st quartile (Q1) and 3rd quartile (Q3) of the data need to be calculated to set the limit on the boxplot (see picture below). In addition, interquartile range (IQR), the distance between the upper quartile (Q3) and the lower quartile (Q1) is needed to determine the inner and outer fence. This method is especially easy to use for small data sets since the quartiles (Q1 and Q3) and interquartile (IQR) can be determined very quickly.



Below are the steps and formulas of constructing a boxplot for a data set

1. Calculating the median (Me) = the $\left(\frac{(n+1)}{2}\right)th$ observation in the data set.
2. Calculating the 1st quartile (Q_1) = the $\left(\frac{(n+1)}{4}\right)th$ observation in the data set.
3. Calculating the 3rd quartile (Q_3) = the $\left(\frac{3(n+1)}{4}\right)th$ observation in the data set.
4. Calculating the Inter Quartile Range (IQR) = $Q_3 - Q_1$
5. Lower Inner Fence is calculated as (LIF) = Q_1 - 1.5 (IQR)
6. Upper Inner Fence = Q3 + 1.5 (IQR)
7. Lower Outer Fence = Q3 - 3 (IQR)
8. Upper Outer Fence = Q3 + 3(IQR)
9. Construct a box on the axis with Q1 and Q3 located at the lower corners. The base width is equal to IQR. Draw a vertical line inside the box to locate the median.
10. Locate inner fences a distance of 1.5 (IQR) below Q1 and above Q3, and locate outer fences a distance of 3 (IQR) below Q1 and above Q3.
11. Observations that fall between the Lower Inner fence (LIF) and Lower Outer Fence (LOF) or Upper Inner Fence (LIF) and Upper Outer Fence (UOF) are called suspect outliers. Observations that are lower than Lower Outer Fence (LOF) or higher than Upper Outer Fence (UOF) are called highly suspect outliers or definite outliers.

Below is an example of a data set with n=20.

3	5	5	5	5	5	10	10	10	10
10	10	10	10	15	15	15	20	20	50

Using the steps and formulas above, the results are as follows:

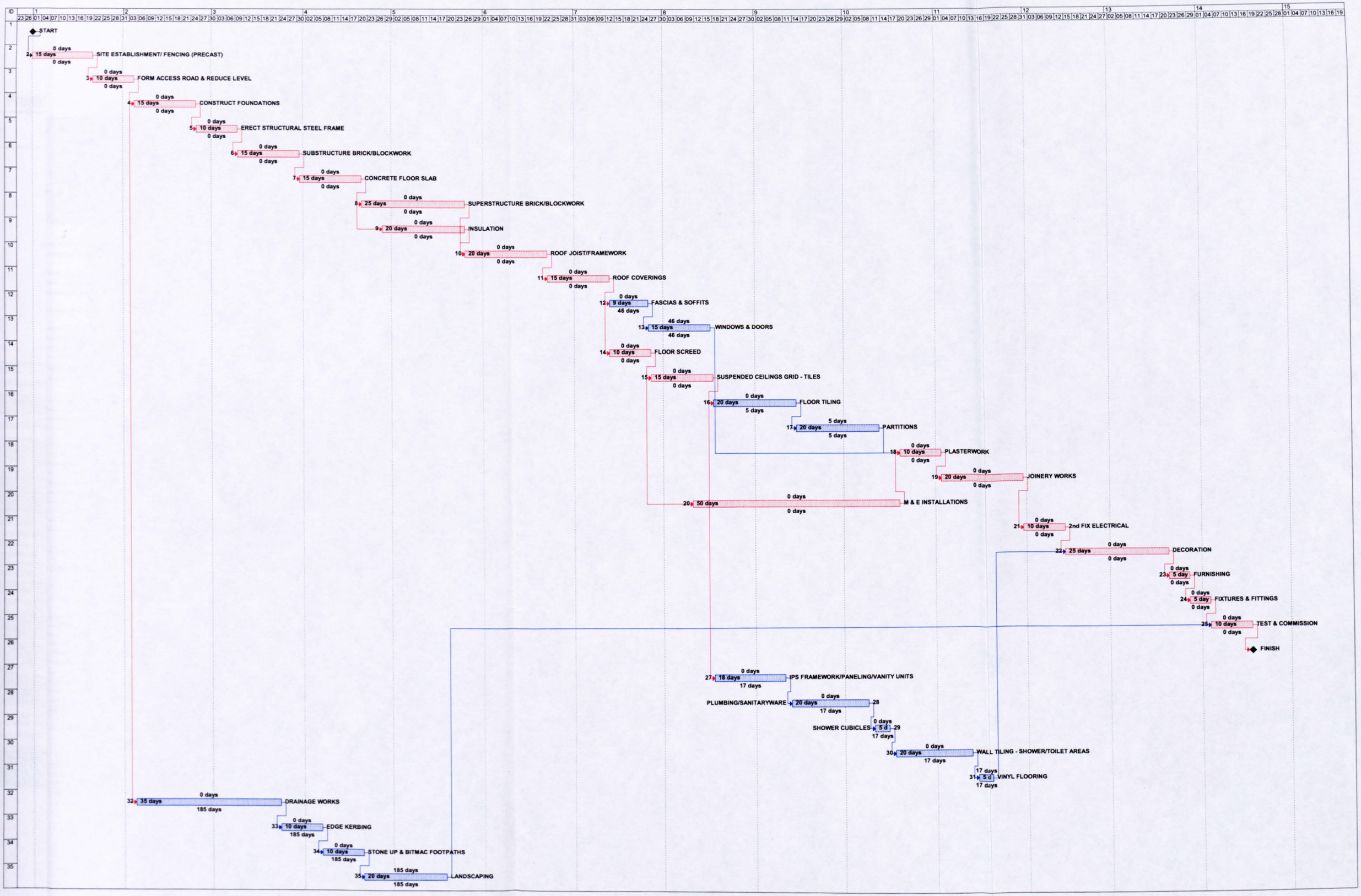
Me=10, Q1=5, Q3=15, LIF=-10, LOF=-25, UIF=30, UOF=45

In this example 50 falls outside the upper outer fence, hence classified as a high suspect or definite outlier.

Appendix A9
Results of the main survey for the simulation

Information flow					Material flows																						Plant/ equipment / temporary workflow					Labour flow				Workflow (Subcontracted work)				
Activies affected by information delays	prob	delay on start date			Materials delivered later than scheduled delivery dates	Time buffer (days)	prob	delay on start date			Material delivered with wrong specifications	prob	delay on start date			Insuffiecient quantity of materials delivered	prob	delay on duration			Materials damaged on arrival	prob	delay on start date			Difficulties in obtaining materials in the market (Q9)	prob	delay on start date			Plant / temporary work in shortage	prob	delay on duration			Skills in shortage during construction	prob	delay on duration				prob	Delay		
		min	most	max				min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max
Ground works	38%	4	11	22	Steel frame	5	9%	3	5	8	Windows & doors	6%	7	12	35	Briks/blocks	15%	3	6	11	Windows & doors	7%	9	15	27	Fixtures & Fittings	38%	9	15	46	Crane	11%	3	6	15	Bricklayers	26%	5	9	16	Mechanical & Ellectrical	12%	4	7	13
Foundation	16%	3	8	12	Steel reinforcement	6	7%	2	4	7	Bricks/blocks	9%	4	7	15	RM Concrete	6%	1	1	2	Shower cubicles	5%	6	10	15	Bricks (special)	14%	7	12	18	Scaffolding	25%	3	7	11	Joiner	28%	4	7	11	Structural steelwork	8%	3	6	14
Finishes & Decoration	11%	4	7	12	Precast concrete element	5	10%	3	6	10	RM Concrete	15%	1	2	3	Timber	16%	2	5	8	Ceiling	7%	3	6	10	Furniture	32%	4	7	18						Plasterer	27%	4	8	13	Roofwork	16%	6	10	16
Steelwork	39%	5	9	14	Bricks/blocks	7	8%	2	5	11	Roofing materials	6%	4	10	12	Furniture	21%	6	9	15	Bricks/Blocks	6%	10	13	16	Claddings	19%	4	9	15						Plumbers	28%	4	8	13	Brickwork	11%	4	7	12
Fixture & Fittings	55%	5	9	14	Windows & doors	11	16%	4	7	13	Timber	12%	6	7	13	Drainage	23%	4	5	8	Drainage	6%	2	3	4	Tiles	20%	1	12	36						Electrician	28%	4	9	13	Groundwork	8%	3	6	11
Joinery / Ironmongery	43%	4	8	18	Roofing materials	4	10%	3	6	10																Joinery (special)	10%	4	10	14						Steel work erectors	16%	3	5	13	Windows & doors	17%	4	10	18
Windows & Doors	31%	4	7	11																																Scaffolders	16%	2	4	7	Finishings & Decoration	14%	3	6	10
																																				Labourer	11%	1	3	6	Foundation	6%	2	5	7
																																				Concrete gang	10%	2	4	7	Concrete floors	13%	1	6	12
																																								Plastering	26%	6	11	18
																																								Drainage	4%	2	4	8

Appendix A10: The original CPM network with links added



Appendix A11
Matrix of activities and supply chain delays

Project activities and SC delays

No	Activities	Information flow					Material flows																												Plant/ equipment / temporary workflow				Labour flow				Workflow (Subcontracted work)				
		Activies affected by information delays	prob	delay on start date			Materials delivered later than scheduled delivery dates	Time buffer (days)	prob	delay on start date			Material delivered with wrong specifications	prob	delay on start date			Insuffiecient quantity of materials delivered	prob	delay on duration			Materials damaged on arrival	prob	delay on start date			Difficulties in obtaining materials in the market (Q9)	prob	delay on start date			Plant / temporary work in shortage	prob	delay on duration			Skills in shortage during construction	prob	delay on duration				prob	Delay		
				min	most	max				min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max			min	most	max
		Ground works	38%	4	11	22	Steel frame	5	9%	3	5	8	Windows & doors	6%	7	12	35	Briks/blocks	15%	3	6	11	Windows & doors	7%	9	15	27	Fixtures & Fittings	38%	9	15	46	Crane	11%	3	6	15	Bricklayers	26%	5	9	16	Mechanical & Electrical	12%	4	7	13
		Foundation	16%	3	8	12	Steel reinforcement	6	7%	2	4	7	Bricks/blocks	9%	4	7	15	RM Concrete	6%	1	1	2	Shower cubicles	5%	6	10	15	Bricks (special)	14%	7	12	18	Scaffolding	25%	3	7	11	Joiner	28%	4	7	11	Structural steelwork	8%	3	6	14
		Finishes & Decoration	11%	4	7	12	Precast concrete element	5	10%	3	6	10	RM Concrete	15%	1	2	3	Timber	16%	2	5	8	Ceiling	7%	3	6	10	Furniture	32%	4	7	18						Plasterer	27%	4	8	13	Roofwork	16%	6	10	16
		Steelwork	39%	5	9	14	Bricks/blocks	7	8%	2	5	11	Roofing materials	6%	4	10	12	Furniture	21%	6	9	15	Bricks/Blocks	6%	10	13	16	Claddings	19%	4	9	15						Plumbers	28%	4	8	13	Brickwork	11%	4	7	12
		Fixture & Fittings	55%	5	9	14	Windows & doors	11	16%	4	7	13	Timber	12%	6	7	13	Drainage	23%	4	5	8	Drainage	6%	2	3	4	Tiles	20%	1	12	36						Electrician	28%	4	9	13	Groundwork	8%	3	6	11
		Joinery / Ironmongery	43%	4	8	18	Roofing materials	4	10%	3	6	10																Joinery (special)	10%	4	10	14						Steel work erectors	16%	3	5	13	Windows & doors	17%	4	10	18
		Windows & Doors	31%	4	7	11																																		Scaffolders	16%	2	4	7	Finishings & Decoration	14%	3	6	10
																																							Labourer	11%	1	3	6	Foundation	6%	2	5	7
																																							Concrete gang	10%	2	4	7	Concrete floors	13%	1	6	12
																																											Plastering	26%	6	11	18
																																											Drainage	4%	2	4	8
1	START																																														
2	SITE ESTABLISHMENT/FENCING						Precast concrete element	5	10%	3	6	10																													Labourer	11%	1	3	6					
3	FORM ACCESS ROAD & REDUCE LEVEL	Ground works	38%	4	11	22																																						Groundwork	8%	3	6	11
4	CONSTRUCT FOUNDATIONS	Foundation	16%	3	8	12							RM Concrete	15%	1	2	3	RM Concrete	6%	1	1	2																			Concrete gang	10%	2	4	7	Foundation	6%	2	5	7
5	ERECT STRUCTURAL STEEL FRAME	Steelwork	39%	5	9	14	Steel frame	5	9%	3	5	8																									Crane	0.11	3	6	15	Steel work erectors	16%	3	5	13	Structural steelwork	8%	3	6	14
6	SUBSTRUCTURE BRICK/BLOCKWORK						Bricks/blocks	7	8%	2	5	11	Bricks/blocks	9%	4	7	15	Briks/blocks	15%	3	6	11	Bricks/Blocks	6%	10	13	16	Bricks	14%	7	12	18						Bricklayers	27%	5	10	17	Brickwork	11%	4	7	12
7	CONCRETE FLOOR SLAB						Steel reinforcement	6	7%	2	4	7	RM Concrete	15%	1	2	3	RM Concrete	6%	1	1	2																			Concrete gang	10%	2	4	7	Concrete floors	13%	1	6	12
8	SUPERSTRUCTURE BRICK/BLOCK						Bricks/blocks	7	8%	2	5	11	Bricks/blocks	9%	4	7	15	Briks/blocks	20%	3	6	11	Bricks/Blocks	6%	10	13	16	Bricks (special)	14%	7	12	18	Scaffolding	0.25	3	7	11	Bricklayers	26%	5	9	16	Brickwork	11%	4	7	12
9	INSULATION																																										Bricklayers	0.26	5	9	16	Brickwork	11%	4	7	12
10	ROOF JOIST/FRAMEWORK						Roofing materials	4	10%	3	6	10	Roofing materials	6%	4	10	12																						Crane	0.11	3	6	15					Roofwork	16%	6	10	16
11	ROOF COVERINGS						Roofing materials	4	10%	3	6	10	Roofing materials	6%	4	10	12																						Scaffolding	0.25	3	7	11	Scaffolders	16%	2	4	7	Roofwork	16%	6	10	16
12	FASCIAS & SOFFITS												Timber	12%	6	7	13	Timber	16%	2	5	8																Scaffolding	0.25	3	7	11	Scaffolders	16%	2	4	7	Roofwork	16%	6	10	16
13	WINDOWS & DOORS	Windows & Doors	31%	4	7	11	Windows & doors	11	16%	4	7	13	Windows & doors	6%	7	12	35						Windows & doors	7%	9	15	27																			Windows & doors	17%	4	10	18
14	FLOOR SCREED																																											Concrete floors	13%	1	6	12
15	SUSPENDED CEILINGS GRID - TILES	Finishes & Decoration	11%	4	7	12																	Ceiling	7%	3	6	10																			Roofwork	16%	6	10	16
16	FLOOR TILING	Finishes & Decoration	11%	4	7	12																						Tiles	20%	1	12	36													Finishings & Decoration	14%	3	6.4	10
17	PARTITIONS	Finishes & Decoration	11%	4	7	12																																		Joiner	28%	4	7	11	Finishings & Decoration	14%	3	6.4	10
18	PLASTERWORK																																							Plasterer	27%	4	8	13	Plastering	26%	6	11	18
19	JOINERY WORKS	Joinery / Ironmongery	43%	4	8	18																						Joinery (special)	10%	4	10	14						Joiner	28%	4	7	11	Finishings & Decoration	14%	3	6.4	10
20	M & E INSTALLATIONS																																							Electrician	28%	4	9	13	Mechanical & Electrical	12%	3.56	7.39	12.71
21	2nd FIX ELECTRICAL																																							Electrician	28%	4	9	13	Mechanical & Electrical	12%	3.56	7.39	12.71
22	DECORATION	Finishes & Decoration	11%	4	7	12																																					Finishings & Decoration	14%	3	6.4	10
23	FURNISHING	Finishes & Decoration	11%	4	7	12																																					Finishings & Decoration	14%	3	6.4	10
24	FIXTURES & FITTINGS	Fixture & Fittings	55%	5	9	14												Furniture	21%	6	9	15						Furniture	32%	4	7	18													Finishings & Decoration	14%	3	6.4	10
25	TEST & COMMISSION																											Fixtures & Fittings	38%	9	15	46						Joiner	28%	4	7	11	Finishings & Decoration	14%	3	6.4	10
26	FINISH																																														
27	IPS FRAMEWORK/PANELING/VANITY UNITS																																										Plumbers	28%	4	8	13					
28	PLUMBING/SANITARYWARE																																										Plumbers	28%	4	8	13					
29	SHOWER CUBICLES																																														
30	WALL TILING - SHOWER/TOILET AREAS	Finishes & Decoration	11%	4	7	12																	Shower cubicles	5%	6	10	15																									
31	VINYL FLOORING	Finishes & Decoration	11%	4	7	12																						Tiles	20%	1	12	36													Finishings & Decoration	14%	3	6.4	10
32	DRAINAGE WORKS	Ground works	38%	4	11	22												Drainage	23%	4	5	8	Drainage	6%	2	3	4																									
33	EDGE KERBING																																											Labourer	11%	1	3	6	Drainage	4%	2	4	8
34	STONE UP & BITMAC FOOTPATHS	Ground works	38%	4	11	22																																					Labourer	11%	1	3	6					
35	LANDSCAPING	Ground works	38%	4	11	22																																					Labourer	11%	1	3	6	Groundwork	8%	3	6	11

Appendix B
Basic simulation models

Copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(1a/b) O_MC_All (TB/NTB)

Name	Description	Rem Duration	Probability Task Exists	Duration Risk
1	**START**	0		
2	**SITE ESTABLISHMENT/ FENCING (PRECAST)**	15		
00003	Late delivery: Precast fencing	0	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00006	Skill shortages: Labourer	0	11%	BetaPert(1,3,6)
3	**FORM ACCESS ROAD & REDUCE LEVEL**	10		
00001	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00008	FORM ACCESS ROAD & REDUCE LEVEL	10		
4	**CONSTRUCT FOUNDATIONS**	15		
00010	Info/approval from client/architect	0	16%	BetaPert(3,8,12)
00011	CONSTRUCT FOUNDATIONS	15		
00012	Delivery with wrong specs: RM Concrete	0	15%	BetaPert(1,2,3)
00013	Delivery with insufficient quantity: RM Concrete	0	6%	BetaPert(1,1,2)
00014	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
5	**ERECT STRUCTURAL STEEL FRAME**	20		
00500	Dummy	0		
00800	Info/approval from client/architect	0	0%	BetaPert(6,8,12)
00900	Late delivery: steel frames	0	15%	BetaPert(3,5,8)
00016	Info/approval from client/architect	0	100%	BetaPert(6,8,12)
00017	Late delivery: steel frames	0	235%	BetaPert(3,5,8)
00018	ERECT STRUCTURAL STEEL FRAME	15		
00019	Skill shortages: Steel work erectors	0	16%	BetaPert(3,5,13)
00020	Shortages: Cranes	0	11%	BetaPert(3,6,15)
6	**SUBSTRUCTURE BRICKWORK/BLOCKWORK**	22		
0120	Dummy	0		
00021	Difficulty in finding in the market: Bricks/blocks	0	0%	BetaPert(7,12,18)
00022	Late delivery: Bricks/blocks	0	8%	BetaPert(2,5,11)
0100	Difficulty in finding in the market: Bricks/blocks	0	100%	BetaPert(7,12,18)
0110	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
00025	SUBSTRUCTURE BRICK/BLOCKWORK	15		
00024	Delivery with wrong specs: Bricks	0	9%	BetaPert(4,7,15)
00026	Materials damaged on arrival: Bricks/blocks	0	6%	BetaPert(10,13,16)
00027	Delivery with insufficient quantity	0	15%	BetaPert(3,6,11)
00028	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
7	**CONCRETE FLOOR SLAB**	21		
00030	Late delivery: steel reinforcement	0	6%	BetaPert(2,4,7)
00032	CONCRETE FLOOR SLAB	15		
00034	Delivery with wrong specs: RM Concrete	0	15%	BetaPert(1,2,3)
00035	Delivery with insufficient quantity: RM Concrete	0	6%	BetaPert(1,1,2)
00036	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
8	**SUPERSTRUCTURE BRICK/BLOCKWORK**	32		
0130	Dummy	0		
0140	Difficulty in finding in the market: Bricks/blocks	0	0%	BetaPert(7,12,18)
015C	Late delivery: Bricks/blocks	0	8%	BetaPert(2,5,11)
0160	Difficulty in finding in the market: Bricks/blocks	0	100%	BetaPert(7,12,18)
0170	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
00038	SUPERSTRUCTURE BRICK/BLOCKWORK	25		
00039	Delivery with wrong specs: Bricks/blocks	0	9%	BetaPert(4,7,15)
00040	Materials damaged on arrival: Bricks/blocks	0	6%	BetaPert(10,13,16)
00041	Delivery with insufficient quantity: Bricks/blocks	0	15%	BetaPert(3,6,11)
00042	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
00043	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
9	**INSULATION**	20		
00045	INSULATION	20		
00046	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
10	**ROOF JOIST/FRAMEWORK**	24		
00047	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00050	ROOF JOIST/FRAMEWORK	20		
00048	Delivery with wrong specs: Roofing materials	0	6%	BetaPert(4,10,12)
00051	Plant shortages: Crane	0	11%	BetaPert(3,6,15)
11	**ROOF COVERINGS**	15		
00052	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00053	ROOF COVERINGS	15		
00054	Delivery with wrong specs: Roofing materials	0	6%	BetaPert(4,10,12)
00055	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00056	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
12	**FASCIAS & SOFFITS**	9		
00057	FASCIAS & SOFFITS	9		
00058	Delivery with wrong specs: Timber	0	12%	BetaPert(6,7,13)
00059	Delivery with insufficient quantity: Timber	0	16%	BetaPert(2,5,8)
00060	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00061	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
13	**WINDOWS & DOORS**	25		
0180	Dummy	0		
00062	Info/approval from client/architect	0	0%	BetaPert(4,7,11)
00063	Late delivery: Windows & Doors	0	16%	BetaPert(4,7,13)
0190	Info/approval from client/architect	0	100%	BetaPert(4,7,11)
0200	Late delivery: Windows & Doors	0	35%	BetaPert(4,7,13)
00064	WINDOWS & DOORS	15		
00065	Delivery with wrong specs: Windows & Doors	0	6%	BetaPert(7,12,35)
00066	Materials damaged on arrival: Windows & Doors	0	7%	BetaPert(9,15,27)
14	**FLOOR SCREED**	10		
00071	FLOOR SCREED	10		
15	**SUSPENDED CEILINGS GRID - TILES**	15		
0220	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00072	SUSPENDED CEILINGS GRID - TILES	15		
00073	Materials damaged on arrival: Ceiling tiles	0	20%	BetaPert(3,6,10)
16	**FLOOR TILING**	20		
00076	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00077	Difficult to find in the market: Tiles	0	20%	BetaPert(1,12,36)
00078	FLOOR TILING	20		
17	**PARTITIONS**	20		
0230	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00080	PARTITIONS	20		
00081	Skill shortages: Joiner	0	28%	BetaPert(4,7,11)
18	**PLASTERWORK**	10		
00082	PLASTERWORK	10		
00084	Skill shortages: Plasterers	0	27%	BetaPert(4,8,13)
19	**JOINERY WORKS**	20		
00086	Info from Client/Architect: Joinery/Ironmongery	0	43%	BetaPert(4,8,18)
00087	Difficult to find in the market: Joinery	0	10%	BetaPert(4,10,14)
00088	JOINERY WORKS	20		
00085	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
20	**M & E INSTALLATIONS**	50		
00090	M & E INSTALLATIONS	50		
00092	Skill shortages: Electrician	0	28%	BetaPert(4,9,13)
21	**2nd FIX ELECTRICAL**	10		
00094	2nd FIX ELECTRICAL	10		
00096	Skill shortages: Electrician	0	28%	BetaPert(4,9,13)
22	**DECORATION**	25		
00097	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00098	DECORATION	25		
23	**FURNISHING**	5		
0240	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00100	Difficult to find in the market: Furniture	0	32%	BetaPert(4,7,18)
00102	FURNISHING	5		
00101	Delivery with insufficient quantity: Furniture	0	21%	BetaPert(6,9,15)
24	**FIXTURES & FITTINGS**	5		
00104	Info from Client/Architect: Fixtures & Fittings	0	55%	BetaPert(5,9,14)
00105	Difficult to find in the market: Fixtures & Fittings	0	38%	BetaPert(9,15,48)
00106	FIXTURES & FITTINGS	5		
00107	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
25	**TEST & COMMISSION**	10		
00109	TEST & COMMISSION	10		
26	**FINISH**	0		
27	**IPS FRAMEWORK/PANELING/VANITY UNITS**	18		
00112	IPS FRAMEWORK/PANELING/VANITY UNITS	18		
00113	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
28	**PLUMBING/SANITARYWARE**	20		
00115	PLUMBING/SANITARYWARE	20		
00116	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
29	**SHOWER CUBICLES**	5		
00118	SHOWER CUBICLES	5		
0010	Materials damaged on arrival: Shower cubicles	0	5%	BetaPert(6,10,15)
30	**WALL TILING - SHOWER/TOILET AREAS**	20		
00120	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00121	Difficult to find in the market: Tiles	0	20%	BetaPert(1,12,36)
00122	WALL TILING - SHOWER/TOILET AREAS	20		
31	**VINYL FLOORING**	5		
0210	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00124	VINYL FLOORING	5		
32	**DRAINAGE WORKS**	35		
00126	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00128	DRAINAGE WORKS	35		
00127	Delivery with insufficient quantity: Drainage	0	23%	BetaPert(4,5,8)
0040	Materials damaged on arrival: drainage	0	6%	BetaPert(2,3,4)
00129	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
33	**EDGE KERBING**	10		
00131	EDGE KERBING	10		
00132	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
34	**STONE UP & BITMAC FOOTPATHS**	10		
0250	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00134	STONE UP & BITMAC FOOTPATHS	10		
00135	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
35	**LANDSCAPING**	20		
00137	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00138	LANDSCAPING	20		
00139	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
TOTALS				

Created by: Jati Hatmoko
Report printed on: 08/Aug/07

MSP Risk Inputs
Page 1 of 1

Copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(1c/d) P_MC_All (TB/NTB)

Name	Description	Rem Duration	Probability Task Exists	Duration Risk
1	START	0		
2	SITE ESTABLISHMENT/ FENCING (PRE	15		
00003	Late delivery: Precast fencing	0	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING	15		
00005	Skill shortages: Labourer	0	11%	BetaPert(1,3,6)
3	FORM ACCESS ROAD & REDUCE LEVE	10		
00007	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00008	FORM ACCESS ROAD & REDUCE	10		
4	CONSTRUCT FOUNDATIONS	15		
00010	Info/approval from client/architect	0	16%	BetaPert(3,8,12)
00011	Delivery with wrong specs: RM Conc	0	15%	BetaPert(1,2,3)
00012	Delivery with insufficient quantity: RM	0	6%	BetaPert(1,1,2)
00013	CONSTRUCT FOUNDATIONS	15		
00014	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
5	ERECT STRUCTURAL STEEL FRAME	20		
0050	Dummy	0		
0080	Info/approval from client/architect	0	0%	BetaPert(6,8,12)
0090	Late delivery: steel frames	0	15%	BetaPert(3,5,8)
0100	Info/approval from client/architect	0	100%	BetaPert(6,8,12)
0110	Late delivery: steel frames	0	23%	BetaPert(3,5,8)
00018	ERECT STRUCTURAL STEEL FRA	15		
00019	Skill shortages: Steel work erectors	0	16%	BetaPert(3,5,13)
00020	Shortages: Cranes	0	11%	BetaPert(3,6,15)
6	SUBSTRUCTURE BRICKWORK/BLOCKW	22		
0120	Dummy	0		
0130	Difficulty in finding in the market: Bric	0	0%	BetaPert(7,12,18)
0140	Late delivery: Bricks/blocks	0	8%	BetaPert(2,5,11)
0150	Difficulty in finding in the market: Bric	0	100%	BetaPert(7,12,18)
0160	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
00024	Delivery with wrong specs: Bricks	0	9%	BetaPert(4,7,15)
00025	SUBSTRUCTURE BRICK/BLOCKW	15		
00026	Materials damaged on arrival: Bricks	0	6%	BetaPert(10,13,16)
00027	Delivery with insufficient quantity	0	15%	BetaPert(3,6,11)
00028	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
7	CONCRETE FLOOR SLAB	21		
00030	Late delivery: steel reinforcement	0	8%	BetaPert(2,4,7)
00031	Delivery with wrong specs: RM Conc	0	15%	BetaPert(1,2,3)
00032	CONCRETE FLOOR SLAB	15		
00033	Delivery with insufficient quantity: RM	0	6%	BetaPert(1,1,2)
00034	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
8	SUPERSTRUCTURE BRICK/BLOCKWOI	32		
0170	Dummy	0		
0180	Difficulty in finding in the market: Bric	0	0%	BetaPert(7,12,18)
0190	Late delivery: Bricks/blocks	0	8%	BetaPert(2,5,11)
0200	Difficulty in finding in the market: Bric	0	100%	BetaPert(7,12,18)
0210	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
00038	Delivery with wrong specs: Bricks/blc	0	9%	BetaPert(4,7,15)
00039	SUPERSTRUCTURE BRICK/BLOCI	25		
00040	Materials damaged on arrival: Bricks	0	6%	BetaPert(10,13,16)
00041	Delivery with insufficient quantity: Br	0	15%	BetaPert(3,6,11)
00042	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
00043	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
9	INSULATION	20		
00045	INSULATION	20		
00046	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
10	ROOF JOIST/FRAMEWORK	24		
00048	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00049	Delivery with wrong specs: Roofing	0	6%	BetaPert(4,10,12)
00050	ROOF JOIST/FRAMEWORK	20		
00051	Plant shortages: Crane	0	11%	BetaPert(3,6,15)
11	ROOF COVERINGS	15		
00053	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00054	Delivery with wrong specs: Roofing	0	6%	BetaPert(4,10,12)
00055	ROOF COVERINGS	15		
00056	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00057	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
12	FASCIAS & SOFFITS	9		
00059	Delivery with wrong specs: Timber	0	12%	BetaPert(6,7,13)
00060	FASCIAS & SOFFITS	9		
00061	Delivery with insufficient quantity: Tir	0	16%	BetaPert(2,6,8)
00062	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00063	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
13	WINDOWS & DOORS	25		
0220	Dummy	0		
0230	Info/approval from client/architect	0	0%	BetaPert(4,7,11)
0240	Late delivery: Windows & Doors	0	16%	BetaPert(4,7,13)
0250	Info/approval from client/architect	0	100%	BetaPert(4,7,11)
0260	Late delivery: Windows & Doors	0	35%	BetaPert(4,7,13)
00067	Delivery with wrong specs: Windows	0	6%	BetaPert(7,12,35)
00068	Materials damaged on arrival: Windc	0	7%	BetaPert(9,15,27)
00069	WINDOWS & DOORS	15		
14	FLOOR SCREED	10		
00071	FLOOR SCREED	10		
15	SUSPENDED CEILINGS GRID - TILES	15		
0270	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00073	Materials damaged on arrival: Ceiling	0	20%	BetaPert(3,6,10)
00074	SUSPENDED CEILINGS GRID - TIL	15		
16	FLOOR TILING	20		
00076	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00077	Difficult to find in the market: Tiles	0	20%	BetaPert(1,12,36)
00078	FLOOR TILING	20		
17	PARTITIONS	20		
0280	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00080	PARTITIONS	20		
00081	Skill shortages: Joiner	0	28%	BetaPert(4,7,11)
18	PLASTERWORK	10		
00083	PLASTERWORK	10		
00084	Skill shortages: Plasterers	0	27%	BetaPert(4,8,13)
19	JOINERY WORKS	20		
00086	Info from Client/Architect: Joinery/Iro	0	43%	BetaPert(4,8,18)
00087	Difficult to find in the market: Joinery	0	10%	BetaPert(4,10,14)
00088	JOINERY WORKS	20		
00089	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
20	M & E INSTALLATIONS	50		
00091	M & E INSTALLATIONS	50		
00092	Skill shortages: Electrician	0	28%	BetaPert(4,9,13)
21	2nd FIX ELECTRICAL	10		
00094	2nd FIX ELECTRICAL	10		
00096	Skill shortages: Electrician	0	28%	BetaPert(4,9,13)
22	DECORATION	25		
00097	Info from Client/Architect: Finishes &	0	11%	BetaPert(4,7,12)
00098	DECORATION	25		
23	FURNISHING	5		
0290	Info from Client/Architect: Finishes &	0	11%	BetaPert(4,7,12)
00100	Difficult to find in the market: Furnitu	0	32%	BetaPert(4,7,18)
00101	Delivery with insufficient quantity: Fu	0	21%	BetaPert(6,9,15)
00102	FURNISHING	5		
24	FIXTURES & FITTINGS	5		
00104	Info from Client/Architect: : Fixtures	0	55%	BetaPert(5,9,14)
00105	Difficult to find in the market: Fixture	0	38%	BetaPert(9,15,46)
00106	FIXTURES & FITTINGS	5		
00107	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
25	TEST & COMMISSION	10		
00109	TEST & COMMISSION	10		
26	FINISH	0		
27	IPS FRAMEWORK/PANELING/VANITY U	15		
00112	IPS FRAMEWORK/PANELING/VAN	15		
00113	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
28	PLUMBING/SANITARYWARE	20		
00115	PLUMBING/SANITARYWARE	20		
00116	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
29	SHOWER CUBICLES	5		
0010	Materials damaged on arrival: Show	0	5%	BetaPert(6,10,15)
00118	SHOWER CUBICLES	5		
30	WALL TILING - SHOWER/TOILET AREA	20		
00120	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00121	Difficult to find in the market: Tiles	0	20%	BetaPert(1,12,36)
00122	WALL TILING - SHOWER/TOILET A	20		
31	VINYL FLOORING	5		
0300	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00124	VINYL FLOORING	5		
32	DRAINAGE WORKS	35		
00126	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00127	Delivery with insufficient quantity: Dr	0	23%	BetaPert(4,5,8)
0040	Materials damaged on arrival: drainag	0	6%	BetaPert(2,3,4)
00128	DRAINAGE WORKS	35		
00129	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
33	EDGE KERBING	10		
00131	EDGE KERBING	10		
00132	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
34	STONE UP & BITMAC FOOTPATHS	10		
0310	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00134	STONE UP & BITMAC FOOTPATH	10		
00135	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
35	LANDSCAPING	20		
00137	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00138	LANDSCAPING	20		
00139	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
TOTAL 0				

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

Copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(11a/b) O/P_SS_Work_All (TB-NTB)

Name	Description	Probability Task Exists	Duration Risk
1	START		
2	SITE ESTABLISHMENT/ FENCING (PREC		
00003	Late delivery: Precast fencing	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING (PR		
00005	Skill shortages: Labourer	11%	BetaPert(1,3,6)
3	FORM ACCESS ROAD & REDUCE LEVEL		
00007	Info/approval from client/architect	38%	BetaPert(4,11,22)
00008	FORM ACCESS ROAD & REDUCE LEV		
0010	SC: Groundwork	8%	BetaPert(3,6,11)
4	CONSTRUCT FOUNDATIONS		
00010	Info/approval from client/architect	16%	BetaPert(3,8,12)
00013	CONSTRUCT FOUNDATIONS		
00014	SC: Foundation	6%	BetaPert(2,5,7)
5	ERECT STRUCTURAL STEEL FRAME		
00016	Info/approval from client/architect	43%	BetaPert(6,8,12)
00018	ERECT STRUCTURAL STEEL FRAME		
00020	SC: Steelwork	8%	BetaPert(3,6,14)
6	SUBSTRUCTURE BRICKWORK/BLOCKW		
00025	SUBSTRUCTURE BRICK/BLOCKWOR		
00026	SC: Bricks/blockwork	11%	BetaPert(4,7,12)
7	CONCRETE FLOOR SLAB		
00032	CONCRETE FLOOR SLAB		
00033	SC: Concrete floor	13%	BetaPert(1,6,12)
8	SUPERSTRUCTURE BRICK/BLOCKWOR		
00039	SUPERSTRUCTURE BRICK/BLOCKWO		
00040	SC: Bricks/blockwork	11%	BetaPert(4,7,12)
9	INSULATION		
00045	INSULATION		
0140	SC: Bricks/blockwork	11%	BetaPert(4,7,12)
10	ROOF JOIST/FRAMEWORK		
00050	ROOF JOIST/FRAMEWORK		
00051	SC: Roofwork	16%	BetaPert(6,10,16)
11	ROOF COVERINGS		
00055	ROOF COVERINGS		
00056	SC: Roofwork	16%	BetaPert(6,10,16)
12	FASCIAS & SOFFITS		
00060	FASCIAS & SOFFITS		
00061	SC: Roofwork	16%	BetaPert(6,10,16)
13	WINDOWS & DOORS		
00065	Info/approval from client/architect	31%	BetaPert(4,7,11)
00069	WINDOWS & DOORS		
0020	SC: Windows & Doors	17%	BetaPert(4,10,18)
14	FLOOR SCREED		
00071	FLOOR SCREED		
0030	SC: Concrete floor	13%	BetaPert(1,6,12)
15	SUSPENDED CEILINGS GRID - TILES		
0160	Info/approval from client/architect	11%	BetaPert(4,7,12)
00074	SUSPENDED CEILINGS GRID - TILES		
0060	SC: Roofwork	16%	BetaPert(6,10,16)
16	FLOOR TILING		
00076	Info/approval from client/architect	11%	BetaPert(4,7,12)
00078	FLOOR TILING		
0040	SC: Finishings & Decoration	14%	BetaPert(3,6,10)
17	PARTITIONS		
0170	Info/approval from client/architect	11%	BetaPert(4,7,12)
00080	PARTITIONS		
0130	SC: Finishings & Decoration	14%	BetaPert(3,6,10)
18	PLASTERWORK		
00083	PLASTERWORK		
00084	SC: Plasterworks	26%	BetaPert(6,11,18)
19	JOINERY WORKS		
00086	Info from Client/Architect: Joinery/Ironmo	43%	BetaPert(4,8,18)
00088	JOINERY WORKS		
0080	SC: Finishings & Decoration	14%	BetaPert(3,6,10)
20	M & E INSTALLATIONS		
00091	M & E INSTALLATIONS		
00092	SC: M&E	12%	BetaPert(4,7,13)
21	2nd FIX ELECTRICAL		
00094	2nd FIX ELECTRICAL		
00095	SC: M&E	12%	BetaPert(4,7,13)
22	DECORATION		
00097	Info from Client/Architect: Finishes & Dec	11%	BetaPert(4,7,12)
00098	DECORATION		
0050	SC: Finishings & decoration	14%	BetaPert(3,6,10)
23	FURNISHING		
0180	Info from Client/Architect: Finishes & Dec	11%	BetaPert(4,7,12)
00102	FURNISHING		
0090	SC: Finishings & decoration	14%	BetaPert(3,6,10)
24	FIXTURES & FITTINGS		
00104	Info from Client/Architect: : Fixtures & Fit	55%	BetaPert(5,9,14)
00106	FIXTURES & FITTINGS		
0100	SC: Finishings & decoration	14%	BetaPert(3,6,10)
25	TEST & COMMISSION		
00109	TEST & COMMISSION		
26	FINISH		
27	IPS FRAMEWORK/PANELING/VANITY UI		
00112	IPS FRAMEWORK/PANELING/VANITY		
00113	Skill shortages: Plumbers	28%	BetaPert(4,8,13)
28	PLUMBING/SANITARYWARE		
00115	PLUMBING/SANITARYWARE		
00116	Skill shortages: Plumbers	28%	BetaPert(4,8,13)
29	SHOWER CUBICLES		
00118	SHOWER CUBICLES		
0070	Materials damaged on arrival: Shower cu	5%	BetaPert(6,10,15)
30	WALL TILING - SHOWER/TOILET AREAS		
00120	Info/approval from client/architect	11%	BetaPert(4,7,12)
00122	WALL TILING - SHOWER/TOILET AREA		
0110	SC: Finishings & decoration	14%	BetaPert(3,6,10)
31	VINYL FLOORING		
0150	Info/approval from client/architect	11%	BetaPert(4,7,12)
00124	VINYL FLOORING		
0120	SC: Finishings & decoration	14%	BetaPert(3,6,10)
32	DRAINAGE WORKS		
00126	Info from Client/Architect	38%	BetaPert(4,11,22)
00128	DRAINAGE WORKS		
00129	SC: Drainage works	4%	BetaPert(2,4,8)
33	EDGE KERBING		
00131	EDGE KERBING		
00132	Skill shortages: Labourers	11%	BetaPert(1,3,6)
34	STONE UP & BITMAC FOOTPATHS		
0190	Info from Client/Architect	38%	BetaPert(4,11,22)
00134	STONE UP & BITMAC FOOTPATHS		
00135	SC: Groundwork	8%	BetaPert(3,6,11)
35	LANDSCAPING		
00137	Info from Client/Architect	38%	BetaPert(4,11,22)
00138	LANDSCAPING		
00139	SC: Groundwork	8%	BetaPert(3,6,11)
TOTALS			

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

Copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(12a/b) O_SS_sub (TB/NTB)

Name	Description	Rem duration	Probability Task Exists	Duration Risk
1	**START**	0		
2	**SITE ESTABLISHMENT/ FENCING (PRECAST)**	15		
00001	Late delivery: Precast fencing	0	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00005	Skill shortages: Labourer	0	11%	BetaPert(1,3,6)
3	**FORM ACCESS ROAD & REDUCE LEVEL**	10		
00002	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00008	FORM ACCESS ROAD & REDUCE LEVEL	10		
02600	SC: Groundwork	0	8%	BetaPert(3,6,11)
4	**CONSTRUCT FOUNDATIONS**	15		
00010	Info/approval from client/architect	0	16%	BetaPert(3,8,12)
00013	CONSTRUCT FOUNDATIONS	15		
00060	SC: Foundation	0	6%	BetaPert(2,5,7)
5	**ERECT STRUCTURAL STEEL FRAME**	20		
00500	Dummy	0	0%	BetaPert(6,8,12)
00800	Info/approval from client/architect	0	15%	BetaPert(3,5,8)
00900	Late delivery: steel frames	0	100%	BetaPert(6,8,12)
00016	Info/approval from client/architect	0	23%	BetaPert(3,5,8)
00017	Late delivery: steel frames	0		
00018	ERECT STRUCTURAL STEEL FRAME	15	16%	BetaPert(3,5,13)
00019	Skill shortages: Steel work erectors	0	11%	BetaPert(3,6,15)
00020	Shortages: Cranes	0		
6	**SUBSTRUCTURE BRICKWORK/BLOCKWORK**	25	0%	BetaPert(7,12,18)
01200	Dummy	0	8%	BetaPert(2,5,11)
00021	Difficulty in finding in the market: Bricks/blocks	0	100%	BetaPert(7,12,18)
00022	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
01000	Difficulty in finding in the market: Bricks/blocks	0		
01100	Late delivery: Bricks/blocks	0	9%	BetaPert(4,7,15)
00025	SUBSTRUCTURE BRICK/BLOCKWORK	15	6%	BetaPert(10,13,16)
00024	Delivery with wrong specs: Bricks	0	15%	BetaPert(3,6,11)
00026	Materials damaged on arrival: Bricks/blocks	0	26%	BetaPert(5,9,16)
00027	Delivery with insufficient quantity	0	25%	BetaPert(3,7,11)
00028	Skill shortages: Bricklayers	0		
7	**CONCRETE FLOOR SLAB**	15	26%	BetaPert(5,9,16)
00030	CONCRETE FLOOR SLAB	15		
00700	SC: Concrete floor	0		
8	**SUPERSTRUCTURE BRICK/BLOCKWORK**	32	13%	BetaPert(1,6,12)
01300	Dummy	0		
01400	Difficulty in finding in the market: Bricks/blocks	0	0%	BetaPert(7,12,18)
01500	Late delivery: Bricks/blocks	0	8%	BetaPert(2,5,11)
01600	Difficulty in finding in the market: Bricks/blocks	0	100%	BetaPert(7,12,18)
01700	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
00035	SUPERSTRUCTURE BRICK/BLOCKWORK	25		
00036	Delivery with wrong specs: Bricks/blocks	0	9%	BetaPert(4,7,15)
00040	Materials damaged on arrival: Bricks/blocks	0	6%	BetaPert(10,13,16)
00041	Delivery with insufficient quantity: Bricks/blocks	0	15%	BetaPert(3,6,11)
00042	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
00043	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
9	**INSULATION**	20		
00045	INSULATION	20	26%	BetaPert(5,9,16)
00046	Skill shortages: Bricklayers	0		
10	**ROOF JOIST/FRAMEWORK**	24	4%	BetaPert(3,6,10)
00047	Late delivery: Roofing materials	0		
00050	ROOF JOIST/FRAMEWORK	20	6%	BetaPert(4,10,12)
00048	Delivery with wrong specs: Roofing materials	0	11%	BetaPert(3,6,15)
00051	Plant shortages: Crane	0		
11	**ROOF COVERINGS**	18	4%	BetaPert(3,6,10)
00052	Late delivery: Roofing materials	0		
00053	ROOF COVERINGS	15	6%	BetaPert(4,10,12)
00054	Delivery with wrong specs: Roofing materials	0	25%	BetaPert(3,7,11)
00055	Shortages: scaffoldings	0	16%	BetaPert(2,4,7)
00057	Skill shortages: Scaffolders	0		
12	**FASCIAS & SOFFITS**	9	12%	BetaPert(6,7,13)
00060	FASCIAS & SOFFITS	9	16%	BetaPert(2,5,8)
00058	Delivery with wrong specs: Timber	0	25%	BetaPert(3,7,11)
00061	Delivery with insufficient quantity: Timber	0	16%	BetaPert(2,4,7)
00062	Shortages: scaffoldings	0		
00063	Skill shortages: Scaffolders	0		
13	**WINDOWS & DOORS**	26	0%	BetaPert(4,7,11)
01800	Dummy	0	16%	BetaPert(4,7,13)
00065	Info/approval from client/architect	0	100%	BetaPert(4,7,11)
00066	Late delivery: Windows & Doors	0	35%	BetaPert(4,7,13)
01900	Info/approval from client/architect	0		
02000	Late delivery: Windows & Doors	0	6%	BetaPert(7,12,35)
00067	WINDOWS & DOORS	15	7%	BetaPert(9,15,27)
00068	Delivery with wrong specs: Windows & Doors	0		
00069	Materials damaged on arrival: Windows & Doors	0	13%	BetaPert(1,6,12)
14	**FLOOR SCREED**	10		
00071	FLOOR SCREED	10	11%	BetaPert(4,7,12)
03000	SC: Concrete floor	0	20%	BetaPert(3,6,10)
15	**SUSPENDED CEILINGS GRID - TILES**	15		
02200	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00074	SUSPENDED CEILINGS GRID - TILES	15	20%	BetaPert(1,12,36)
00073	Materials damaged on arrival: Ceiling tiles	0		
16	**FLOOR TILING**	20	11%	BetaPert(4,7,12)
00076	Info/approval from client/architect	0	28%	BetaPert(4,7,11)
00077	Difficult to find in the market: Tiles	0		
00078	FLOOR TILING	20	27%	BetaPert(4,8,13)
17	**PARTITIONS**	20	43%	BetaPert(4,8,18)
02300	Info/approval from client/architect	0	10%	BetaPert(4,10,14)
00080	PARTITIONS	20		
00081	Skill shortages: Joiner	0	28%	BetaPert(4,7,11)
18	**PLASTERWORK**	10		
00082	PLASTERWORK	10	27%	BetaPert(4,8,13)
00084	Skill shortages: Plasterers	0		
19	**JOINERY WORKS**	20	28%	BetaPert(4,9,13)
00085	Info from Client/Architect: Joinery/Ironmongery	0		
00087	Difficult to find in the market: Joinery	0	28%	BetaPert(4,9,13)
00086	JOINERY WORKS	20		
00088	Skill shortages: Joiners	0	11%	BetaPert(4,7,12)
20	**M & E INSTALLATIONS**	50		
00090	M & E INSTALLATIONS	50	11%	BetaPert(4,7,12)
00092	Skill shortages: Electrician	0	32%	BetaPert(4,7,18)
21	**2nd FIX ELECTRICAL**	10		
00094	2nd FIX ELECTRICAL	10	21%	BetaPert(6,9,15)
00095	Skill shortages: Electrician	0		
22	**DECORATION**	25	55%	BetaPert(5,9,14)
00097	Info from Client/Architect: Finishes & Decoration	0	38%	BetaPert(9,15,46)
00098	DECORATION	25		
23	**FURNISHING**	5	28%	BetaPert(4,7,11)
02400	Info from Client/Architect: Finishes & Decoration	0		
00100	Difficult to find in the market: Furniture	0		
00102	FURNISHING	5		
00101	Delivery with insufficient quantity: Furniture	0		
24	**FIXTURES & FITTINGS**	5		
00104	Info from Client/Architect: : Fixtures & Fittings	0		
00105	Difficult to find in the market: Fixtures & Fittings	0		
00106	FIXTURES & FITTINGS	5		
00107	Skill shortages: Joiners	0		
25	**TEST & COMMISSION**	10		
00109	TEST & COMMISSION	10		
26	**FINISH**	0		
27	**IPS FRAMEWORK/PANELING/VANITY UNITS**	18	28%	BetaPert(4,8,13)
00112	IPS FRAMEWORK/PANELING/VANITY UNITS	18		
00113	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
28	**PLUMBING/SANITARYWARE**	20		
00115	PLUMBING/SANITARYWARE	20	6%	BetaPert(6,10,15)
00114	Skill shortages: Plumbers	0	11%	BetaPert(4,7,12)
29	**SHOWER CUBICLES**	5	20%	BetaPert(1,12,36)
00116	SHOWER CUBICLES	5		
00110	Materials damaged on arrival: Shower cubicles	0		
30	**WALL TILING - SHOWER/TOILET AREAS**	20	11%	BetaPert(4,7,12)
00120	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00121	Difficult to find in the market: Tiles	0		
00122	WALL TILING - SHOWER/TOILET AREAS	20	4%	BetaPert(2,4,8)
31	**VINYL FLOORING**	5		
02100	Info/approval from client/architect	0	11%	BetaPert(1,3,6)
00124	VINYL FLOORING	5		
32	**DRAINAGE WORKS**	35	38%	BetaPert(4,11,22)
00126	Info from Client/Architect	0		
00127	DRAINAGE WORKS	35	8%	BetaPert(3,6,11)
02700	SC: Drainage works	0		
33	**EDGE KERBING**	10	38%	BetaPert(4,11,22)
00131	EDGE KERBING	10		
00132	Skill shortages: Labourers	0	8%	BetaPert(3,6,11)
34	**STONE UP & BITMAC FOOTPATHS**	10		
02500	Info from Client/Architect	0		
00134	STONE UP & BITMAC FOOTPATHS	10		
02800	SC: Groundwork	0		
35	**LANDSCAPING**	20		
00137	Info from Client/Architect	0		
00138	LANDSCAPING	20		
02900	SC: Groundwork	0		
	TOTALS			

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(13a/b) O_SS_sup (TB/NTB)

Name	Description	Rem Duration	Probability Task Exists	Duration Risk
1	START	0		
2	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00003	Late delivery: Precast fencing	0	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00005	Skill shortages: Labourer	0	11%	BetaPert(1,3,6)
3	FORM ACCESS ROAD & REDUCE LEVEL	10		
00007	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00008	FORM ACCESS ROAD & REDUCE LEVEL	10		
4	CONSTRUCT FOUNDATIONS	15		
00010	Info/approval from client/architect	0	16%	BetaPert(3,8,12)
00013	CONSTRUCT FOUNDATIONS	15		
00011	Delivery with wrong specs: RM Concrete	0	15%	BetaPert(1,2,3)
00012	Delivery with insufficient quantity: RM Concrete	0	6%	BetaPert(1,1,2)
00014	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
5	ERECT STRUCTURAL STEEL FRAME	15		
0050	Dummy	0		
00016	ERECT STRUCTURAL STEEL FRAME	15		
0260	SC: Steelwork	0	8%	BetaPert(3,6,14)
6	SUBSTRUCTURE BRICKWORK/BLOCKWORK	15		
00025	SUBSTRUCTURE BRICK/BLOCKWORK	15		
0060	SC: Bricks/blockwork	0	11%	BetaPert(4,7,12)
7	CONCRETE FLOOR SLAB	21		
00030	Late delivery: steel reinforcement	0	6%	BetaPert(2,4,7)
00032	CONCRETE FLOOR SLAB	15		
00031	Delivery with wrong specs: RM Concrete	0	15%	BetaPert(1,2,3)
00033	Delivery with insufficient quantity: RM Concrete	0	6%	BetaPert(1,1,2)
00034	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
8	SUPERSTRUCTURE BRICK/BLOCKWORK	25		
0130	Dummy	0		
00036	SUPERSTRUCTURE BRICK/BLOCKWORK	25		
0280	SC: Bricks/blockwork	0	11%	BetaPert(4,7,12)
9	INSULATION	20		
00045	INSULATION	20		
0290	SC: Bricks/blockwork	0	11%	BetaPert(4,7,12)
10	ROOF JOIST/FRAMEWORK	20		
00050	ROOF JOIST/FRAMEWORK	20		
0080	SC: Roofwork	0	16%	BetaPert(6,10,16)
11	ROOF COVERINGS	15		
00055	ROOF COVERINGS	15		
0300	SC: Roofwork	0	16%	BetaPert(6,10,16)
12	FASCIAS & SOFFITS	9		
00060	FASCIAS & SOFFITS	9		
0310	SC: Roofwork	0	16%	BetaPert(6,10,16)
13	WINDOWS & DOORS	20		
0180	Dummy	0		
00065	Info/approval from client/architect	0	0%	BetaPert(4,7,11)
00066	Late delivery: Windows & Doors	0	16%	BetaPert(4,7,13)
0190	Info/approval from client/architect	0	100%	BetaPert(4,7,11)
0200	Late delivery: Windows & Doors	0	35%	BetaPert(4,7,13)
00068	WINDOWS & DOORS	15		
00067	Delivery with wrong specs: Windows & Doors	0	6%	BetaPert(7,12,35)
00069	Materials damaged on arrival: Windows & Doors	0	7%	BetaPert(9,15,27)
14	FLOOR SCREED	10		
00071	FLOOR SCREED	10		
15	SUSPENDED CEILINGS GRID - TILES	15		
0220	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00074	SUSPENDED CEILINGS GRID - TILES	15		
0320	SC: Roofwork	0	16%	BetaPert(6,10,16)
16	FLOOR TILING	20		
00076	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00077	Difficult to find in the market: Tiles	0	20%	BetaPert(1,12,36)
00078	FLOOR TILING	20		
17	PARTITIONS	20		
0230	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00080	PARTITIONS	20		
00081	Skill shortages: Joiner	0	28%	BetaPert(4,7,11)
18	PLASTERWORK	10		
00083	PLASTERWORK	10		
00084	Skill shortages: Plasterers	0	27%	BetaPert(4,8,13)
19	JOINERY WORKS	20		
00086	Info from Client/Architect: Joinery/Ironmongery	0	43%	BetaPert(4,8,18)
00087	Difficult to find in the market: Joinery	0	10%	BetaPert(4,10,14)
00088	JOINERY WORKS	20		
00089	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
20	M & E INSTALLATIONS	50		
00091	M & E INSTALLATIONS	50		
00092	Skill shortages: Electrician	0	28%	BetaPert(4,9,13)
21	2nd FIX ELECTRICAL	10		
00094	2nd FIX ELECTRICAL	10		
00095	Skill shortages: Electrician	0	28%	BetaPert(4,9,13)
22	DECORATION	25		
00097	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00098	DECORATION	25		
23	FURNISHING	5		
0240	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00100	Difficult to find in the market: Furniture	0	32%	BetaPert(4,7,18)
00102	FURNISHING	5		
00101	Delivery with insufficient quantity: Furniture	0	21%	BetaPert(6,9,15)
24	FIXTURES & FITTINGS	5		
00104	Info from Client/Architect: : Fixtures & Fittings	0	55%	BetaPert(5,9,14)
00105	Difficult to find in the market: Fixtures & Fittings	0	38%	BetaPert(9,15,46)
00106	FIXTURES & FITTINGS	5		
00107	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
25	TEST & COMMISSION	10		
00108	TEST & COMMISSION	10		
26	FINISH	0		
27	IPS FRAMEWORK/PANELING/VANITY UNITS	18		
00112	IPS FRAMEWORK/PANELING/VANITY UNITS	18		
00113	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
28	PLUMBING/SANITARYWARE	20		
00115	PLUMBING/SANITARYWARE	20		
00116	Skill shortages: Plumbers	0	28%	BetaPert(4,8,13)
29	SHOWER CUBICLES	5		
00118	SHOWER CUBICLES	5		
0010	Materials damaged on arrival: Shower cubicles	0	5%	BetaPert(6,10,15)
30	WALL TILING - SHOWER/TOILET AREAS	20		
00120	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00121	Difficult to find in the market: Tiles	0	20%	BetaPert(1,12,36)
00122	WALL TILING - SHOWER/TOILET AREAS	20		
31	VINYL FLOORING	5		
0210	Info/approval from client/architect	0	11%	BetaPert(4,7,12)
00124	VINYL FLOORING	5		
32	DRAINAGE WORKS	35		
00126	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00128	DRAINAGE WORKS	35		
00127	Delivery with insufficient quantity: Drainage	0	23%	BetaPert(4,5,8)
0040	Materials damaged on arrival: drainage	0	6%	BetaPert(2,3,4)
00129	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
33	EDGE KERBING	10		
00131	EDGE KERBING	10		
00132	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
34	STONE UP & BITMAC FOOTPATHS	10		
0250	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00134	STONE UP & BITMAC FOOTPATHS	10		
00135	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
35	LANDSCAPING	20		
00137	Info from Client/Architect	0	38%	BetaPert(4,11,22)
00136	LANDSCAPING	20		
00138	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
TOTALS				

Created by: Jati Hatmoko
Report printed on: 08/Aug/07

MSP Risk Inputs
Page 1 of 1

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(14a/b) O_SS_M&E (TB/NTB)

Name	Description	Rem. Duration	Probability Task Exists	Duration Risk
1	**START**	0		
2	**SITE ESTABLISHMENT/ FENCING (PRECAST)**	15		
00001	Late delivery: Precast fencing	0	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00005	Skill shortages: Labourer	0	11%	BetaPert(1,3,6)
3	**FORM ACCESS ROAD & REDUCE LEVEL**	10		
00001	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00006	FORM ACCESS ROAD & REDUCE LEVEL	10		
4	**CONSTRUCT FOUNDATIONS**	15		
00016	Info/approval from client/architect	0	16%	BetaPert(3,8,12)
00017	CONSTRUCT FOUNDATIONS	15		
00011	Delivery with wrong specs: RM Concrete	0	15%	BetaPert(1,2,3)
00012	Delivery with insufficient quantity: RM Concrete	0	6%	BetaPert(1,1,2)
00014	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
5	**ERECT STRUCTURAL STEEL FRAME**	20		
00500	Dummy	0	0%	BetaPert(6,8,12)
00800	Info/approval from client/architect	0	15%	BetaPert(3,5,8)
00901	Late delivery: steel frames	0	100%	BetaPert(6,8,12)
00016	Info/approval from client/architect	0	23%	BetaPert(3,5,8)
00017	Late delivery: steel frames	0		
00018	ERECT STRUCTURAL STEEL FRAME	15	16%	BetaPert(3,5,13)
00019	Skill shortages: Steel work erectors	0	11%	BetaPert(3,6,15)
00020	Shortages: Cranes	0		
6	**SUBSTRUCTURE BRICKWORK/BLOCKWORK**	22		
0120	Dummy	0	0%	BetaPert(7,12,18)
00022	Difficulty in finding in the market: Bricks/blocks	0	8%	BetaPert(2,5,11)
00023	Late delivery: Bricks/blocks	0	100%	BetaPert(7,12,18)
0100	Difficulty in finding in the market: Bricks/blocks	0	50%	BetaPert(2,5,11)
0110	Late delivery: Bricks/blocks	0		
00025	SUBSTRUCTURE BRICK/BLOCKWORK	15	9%	BetaPert(4,7,15)
00027	Delivery with wrong specs: Bricks	0	6%	BetaPert(10,13,16)
00026	Materials damaged on arrival: Bricks/blocks	0	15%	BetaPert(3,6,11)
00028	Delivery with insufficient quantity	0	25%	BetaPert(5,9,16)
00029	Skill shortages: Bricklayers	0		
7	**CONCRETE FLOOR SLAB**	21	6%	BetaPert(2,4,7)
00030	Late delivery: steel reinforcement	0		
00031	CONCRETE FLOOR SLAB	15	15%	BetaPert(1,2,3)
00032	Delivery with wrong specs: RM Concrete	0	6%	BetaPert(1,1,2)
00033	Delivery with insufficient quantity: RM Concrete	0	10%	BetaPert(2,4,7)
00034	Skill shortages: Concrete gang	0		
8	**SUPERSTRUCTURE BRICK/BLOCKWORK**	35		
0130	Dummy	0		
0140	Difficulty in finding in the market: Bricks/blocks	0	0%	BetaPert(7,12,18)
0150	Late delivery: Bricks/blocks	0	8%	BetaPert(2,5,11)
0160	Difficulty in finding in the market: Bricks/blocks	0	100%	BetaPert(7,12,18)
0170	Late delivery: Bricks/blocks	0	50%	BetaPert(2,5,11)
00035	SUPERSTRUCTURE BRICK/BLOCKWORK	25		
00037	Delivery with wrong specs: Bricks/blocks	0	9%	BetaPert(4,7,15)
00040	Materials damaged on arrival: Bricks/blocks	0	6%	BetaPert(10,13,16)
00041	Delivery with insufficient quantity: Bricks/blocks	0	15%	BetaPert(3,6,11)
00042	Skill shortages: Bricklayers	0	25%	BetaPert(5,9,16)
00043	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
9	**INSULATION**	20		
00045	INSULATION	20	28%	BetaPert(5,9,16)
00046	Skill shortages: Bricklayers	0		
10	**ROOF JOIST/FRAMEWORK**	24		
00048	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00050	ROOF JOIST/FRAMEWORK	20		
00049	Delivery with wrong specs: Roofing materials	0	6%	BetaPert(4,10,12)
00051	Plant shortages: Crane	0	11%	BetaPert(3,6,15)
11	**ROOF COVERINGS**	19		
00052	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00053	ROOF COVERINGS	15		
00054	Delivery with wrong specs: Roofing materials	0	6%	BetaPert(4,10,12)
00056	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00055	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
12	**FASCIAS & SOFFITS**	9		
00057	FASCIAS & SOFFITS	9		
00058	Delivery with wrong specs: Timber	0	12%	BetaPert(6,7,13)
00060	Delivery with insufficient quantity: Timber	0	18%	BetaPert(2,5,8)
00059	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00061	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
13	**WINDOWS & DOORS**	20		
0180	Dummy	0		
00062	Info/approval from client/architect	0	0%	BetaPert(4,7,11)
00063	Late delivery: Windows & Doors	0	16%	BetaPert(4,7,13)
0190	Info/approval from client/architect	0	100%	BetaPert(4,7,11)
0200	Late delivery: Windows & Doors	0	35%	BetaPert(4,7,13)
00066	WINDOWS & DOORS	15		
00065	Delivery with wrong specs: Windows & Doors	0	6%	BetaPert(7,12,35)
00064	Materials damaged on arrival: Windows & Doors	0	7%	BetaPert(9,15,27)
14	**FLOOR SCREED**	10		
00071	FLOOR SCREED	10	11%	BetaPert(4,7,12)
15	**SUSPENDED CEILINGS GRID - TILES**	15		
0220	Info/approval from client/architect	0	20%	BetaPert(3,6,10)
00074	SUSPENDED CEILINGS GRID - TILES	15		
00073	Materials damaged on arrival: Ceiling tiles	0	11%	BetaPert(4,7,12)
16	**FLOOR TILING**	20		
00076	Info/approval from client/architect	0	20%	BetaPert(1,12,36)
00077	Difficult to find in the market: Tiles	0		
00078	FLOOR TILING	20		
17	**PARTITIONS**	20	11%	BetaPert(4,7,12)
0230	Info/approval from client/architect	0		
00080	PARTITIONS	20	28%	BetaPert(4,7,11)
00081	Skill shortages: Joiner	0		
18	**PLASTERWORK**	10		
00083	PLASTERWORK	10	27%	BetaPert(4,8,13)
00084	Skill shortages: Plasterers	0		
19	**JOINERY WORKS**	20	43%	BetaPert(4,8,16)
00086	Info from Client/Architect: Joinery/Ironmongery	0	10%	BetaPert(4,10,14)
00085	Difficult to find in the market: Joinery	0		
00087	JOINERY WORKS	20	28%	BetaPert(4,7,11)
00088	Skill shortages: Joiners	0		
20	**M & E INSTALLATIONS**	50		
00090	M & E INSTALLATIONS	50	12%	BetaPert(4,7,13)
0260	SC: M&E	0		
21	**2nd FIX ELECTRICAL**	10		
00094	2nd FIX ELECTRICAL	10	12%	BetaPert(4,7,13)
0270	SC: M&E	0		
22	**DECORATION**	25		
00095	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00096	DECORATION	25		
23	**FURNISHING**	5		
0240	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00100	Difficult to find in the market: Furniture	0	32%	BetaPert(4,7,18)
00102	FURNISHING	5		
00101	Delivery with insufficient quantity: Furniture	0	21%	BetaPert(6,9,15)
24	**FIXTURES & FITTINGS**	5		
00104	Info from Client/Architect: Fixtures & Fittings	0	55%	BetaPert(6,9,14)
00105	Difficult to find in the market: Fixtures & Fittings	0	38%	BetaPert(9,15,46)
00106	FIXTURES & FITTINGS	5		
00103	Skill shortages: Joiners	0	28%	BetaPert(4,7,11)
25	**TEST & COMMISSION**	10		
00108	TEST & COMMISSION	10		
26	**FINISH**	0		
27	**IPS FRAMEWORK/PANELING/VANITY UNITS**	15		
00112	IPS FRAMEWORK/PANELING/VANITY UNITS	15	28%	BetaPert(4,8,13)
00113	Skill shortages: Plumbers	0		
28	**PLUMBING/SANITARYWARE**	20	28%	BetaPert(4,8,13)
00115	PLUMBING/SANITARYWARE	20		
00116	Skill shortages: Plumbers	0		
29	**SHOWER CUBICLES**	5	5%	BetaPert(6,10,15)
00117	SHOWER CUBICLES	5		
0010	Materials damaged on arrival: Shower cubicles	0		
30	**WALL TILING - SHOWER/TOILET AREAS**	20	11%	BetaPert(4,7,12)
00120	Info/approval from client/architect	0	20%	BetaPert(1,12,36)
0012	Difficult to find in the market: Tiles	0		
00122	WALL TILING - SHOWER/TOILET AREAS	20		
31	**VINYL FLOORING**	5	11%	BetaPert(4,7,12)
0210	Info/approval from client/architect	0		
00124	VINYL FLOORING	5		
32	**DRAINAGE WORKS**	35	38%	BetaPert(4,11,22)
00126	Info from Client/Architect	0	23%	BetaPert(4,5,8)
00128	DRAINAGE WORKS	35	6%	BetaPert(2,3,4)
00127	Delivery with insufficient quantity: Drainage	0	11%	BetaPert(1,3,6)
0040	Materials damaged on arrival: drainage	0		
00125	Skill shortages: Labourers	0	11%	BetaPert(1,3,6)
33	**EDGE KERBING**	10		
0013	EDGE KERBING	10	38%	BetaPert(4,11,22)
00133	Skill shortages: Labourers	0		
34	**STONE UP & BITMAC FOOTPATHS**	10	11%	BetaPert(1,3,6)
0250	Info from Client/Architect	0		
00134	STONE UP & BITMAC FOOTPATHS	10	38%	BetaPert(4,11,22)
00135	Skill shortages: Labourers	0		
35	**LANDSCAPING**	20	11%	BetaPert(1,3,6)
00137	Info from Client/Architect	0		
00138	LANDSCAPING	20		
00139	Skill shortages: Labourers	0		
TOTALS				

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(15a/b) O_SS_fin (TB/NTB)

Name	Description	Rem Duration	Probability Task Exists	Duration Risk
1	START	0		
2	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00001	Late delivery: Precast fencing	0	10%	BetaPert(3,6,10)
00004	SITE ESTABLISHMENT/ FENCING (PRECAST)	15		
00006	Skill shortages: Labourer	0	11%	BetaPert(1,3,6)
3	FORM ACCESS ROAD & REDUCE LEVEL	10		
00007	Info/approval from client/architect	0	38%	BetaPert(4,11,22)
00008	FORM ACCESS ROAD & REDUCE LEVEL	10		
4	CONSTRUCT FOUNDATIONS	15	16%	BetaPert(3,8,12)
00010	Info/approval from client/architect	0		
00011	CONSTRUCT FOUNDATIONS	15	15%	BetaPert(1,2,3)
00011	Delivery with wrong specs: RM Concrete	0	6%	BetaPert(1,1,2)
00012	Delivery with insufficient quantity: RM Concrete	0	10%	BetaPert(2,4,7)
00014	Skill shortages: Concrete gang	0		
5	ERECT STRUCTURAL STEEL FRAME	20		
00500	Dummy	0	0%	BetaPert(6,8,12)
00800	Info/approval from client/architect	0	15%	BetaPert(3,5,8)
00900	Late delivery: steel frames	0	100%	BetaPert(6,8,12)
03800	Info/approval from client/architect	0	23%	BetaPert(3,5,8)
03900	Late delivery: steel frames	0		
00016	ERECT STRUCTURAL STEEL FRAME	15	16%	BetaPert(3,5,13)
00019	Skill shortages: Steel work erectors	0	11%	BetaPert(3,6,15)
00020	Shortages: Cranes	0		
6	SUBSTRUCTURE BRICKWORK/BLOCKWORK	22		
01200	Dummy	0	0%	BetaPert(7,12,18)
03600	Difficulty in finding in the market: Bricks/blocks	0	8%	BetaPert(2,5,11)
03700	Late delivery: Bricks/blocks	0	100%	BetaPert(7,12,18)
01000	Difficulty in finding in the market: Bricks/blocks	0	50%	BetaPert(2,5,11)
01100	Late delivery: Bricks/blocks	0		
00026	SUBSTRUCTURE BRICK/BLOCKWORK	15		
00024	Delivery with wrong specs: Bricks	0	9%	BetaPert(4,7,15)
00026	Materials damaged on arrival: Bricks/blocks	0	6%	BetaPert(10,13,16
00027	Delivery with insufficient quantity	0	15%	BetaPert(3,6,11)
00028	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
7	CONCRETE FLOOR SLAB	21		
00030	Late delivery: steel reinforcement	0	6%	BetaPert(2,4,7)
00032	CONCRETE FLOOR SLAB	15		
00033	Delivery with wrong specs: RM Concrete	0	15%	BetaPert(1,2,3)
00033	Delivery with insufficient quantity: RM Concrete	0	6%	BetaPert(1,1,2)
00034	Skill shortages: Concrete gang	0	10%	BetaPert(2,4,7)
8	SUPERSTRUCTURE BRICK/BLOCKWORK	30		
01300	Dummy	0	0%	BetaPert(7,12,18)
01400	Difficulty in finding in the market: Bricks/blocks	0	8%	BetaPert(2,5,11)
01500	Late delivery: Bricks/blocks	0	100%	BetaPert(7,12,18)
03400	Difficulty in finding in the market: Bricks/blocks	0	50%	BetaPert(2,5,11)
03500	Late delivery: Bricks/blocks	0		
00030	SUPERSTRUCTURE BRICK/BLOCKWORK	25	9%	BetaPert(4,7,15)
00036	Delivery with wrong specs: Bricks/blocks	0	6%	BetaPert(10,13,16
00040	Materials damaged on arrival: Bricks/blocks	0	15%	BetaPert(3,6,11)
00041	Delivery with insufficient quantity: Bricks/blocks	0	26%	BetaPert(5,9,16)
00042	Skill shortages: Bricklayers	0	25%	BetaPert(3,7,11)
00043	Shortages: scaffoldings	0		
9	INSULATION	20	8%	BetaPert(5,9,16)
00045	INSULATION	20		
00046	Skill shortages: Bricklayers	0	26%	BetaPert(5,9,16)
10	ROOF JOIST/FRAMEWORK	24		
00048	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00050	ROOF JOIST/FRAMEWORK	20		
00049	Delivery with wrong specs: Roofing materials	0	6%	BetaPert(4,10,12)
00051	Plant shortages: Crane	0	11%	BetaPert(3,6,15)
11	ROOF COVERINGS	19		
00053	Late delivery: Roofing materials	0	4%	BetaPert(3,6,10)
00056	ROOF COVERINGS	15		
00054	Delivery with wrong specs: Roofing materials	0	6%	BetaPert(4,10,12)
00056	Shortages: scaffoldings	0	25%	BetaPert(3,7,11)
00057	Skill shortages: Scaffolders	0	16%	BetaPert(2,4,7)
12	FASCIAS & SOFFITS	9		
00060	FASCIAS & SOFFITS	9	12%	BetaPert(6,7,13)
00058	Delivery with wrong specs: Timber	0	16%	BetaPert(2,5,8)
00059	Delivery with insufficient quantity: Timber	0	25%	BetaPert(3,7,11)
00062	Shortages: scaffoldings	0	16%	BetaPert(2,4,7)
00063	Skill shortages: Scaffolders	0		
13	WINDOWS & DOORS	25		
00180	Dummy	0	0%	BetaPert(4,7,11)
00065	Info/approval from client/architect	0	16%	BetaPert(4,7,13)
00066	Late delivery: Windows & Doors	0	100%	BetaPert(4,7,11)
04000	Info/approval from client/architect	0	38%	BetaPert(4,7,13)
04100	Late delivery: Windows & Doors	0		
00067	WINDOWS & DOORS	15	6%	BetaPert(7,12,35)
00068	Delivery with wrong specs: Windows & Doors	0	7%	BetaPert(9,15,27)
00069	Materials damaged on arrival: Windows & Doors	0		
14	FLOOR SCREED	10		
00071	FLOOR SCREED	10	11%	BetaPert(4,7,12)
15	SUSPENDED CEILINGS GRID - TILES	15		
02200	Info/approval from client/architect	0	20%	BetaPert(3,6,10)
00074	SUSPENDED CEILINGS GRID - TILES	15		
00073	Materials damaged on arrival: Ceiling tiles	0	11%	BetaPert(4,7,12)
16	FLOOR TILING	20		
00076	Info/approval from client/architect	0	14%	BetaPert(3,6,10)
00078	FLOOR TILING	20		
02700	SC: Finishings & Decoration	0	11%	BetaPert(4,7,12)
17	PARTITIONS	20		
02300	Info/approval from client/architect	0	14%	BetaPert(3,6,10)
00080	PARTITIONS	20		
02800	SC: Finishings & Decoration	0		
18	PLASTERWORK	10		
00085	PLASTERWORK	10	26%	BetaPert(6,11,18)
00600	SC: Plasterworks	0		
19	JOINERY WORKS	20	43%	BetaPert(4,8,18)
00088	Info from Client/Architect: Joinery/Ironmongery	0		
00087	JOINERY WORKS	20	14%	BetaPert(3,6,10)
02900	SC: Finishings & Decoration	0		
20	M & E INSTALLATIONS	30		
00091	M & E INSTALLATIONS	30	28%	BetaPert(4,9,13)
00092	Skill shortages: Electrician	0		
21	2nd FIX ELECTRICAL	10		
00094	2nd FIX ELECTRICAL	10	28%	BetaPert(4,9,13)
00095	Skill shortages: Electrician	0		
22	DECORATION	25		
00097	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00096	DECORATION	25		
00700	SC: Finishings & decoration	0	14%	BetaPert(3,6,10)
23	FURNISHING	5		
02400	Info from Client/Architect: Finishes & Decoration	0	11%	BetaPert(4,7,12)
00102	FURNISHING	5		
03000	SC: Finishings & decoration	0	14%	BetaPert(3,6,10)
24	FIXTURES & FITTINGS	5		
00104	Info from Client/Architect: : Fixtures & Fittings	0	55%	BetaPert(6,9,14)
00106	FIXTURES & FITTINGS	5		
03100	SC: Finishings & decoration	0	14%	BetaPert(3,6,10)
25	TEST & COMMISSION	10		
00108	TEST & COMMISSION	10		
26	FINISH	0		
27	IPS FRAMEWORK/PANELING/VANITY UNITS	18		
00112	IPS FRAMEWORK/PANELING/VANITY UNITS	18	28%	BetaPert(4,8,13)
00111	Skill shortages: Plumbers	0		
28	PLUMBING/SANITARYWARE	20	28%	BetaPert(4,8,13)
00115	PLUMBING/SANITARYWARE	20		
00116	Skill shortages: Plumbers	0		
29	SHOWER CUBICLES	5	5%	BetaPert(6,10,15)
00118	SHOWER CUBICLES	5		
00100	Materials damaged on arrival: Shower cubicles	0		
30	WALL TILING : SHOWER/TOILET AREAS	20	11%	BetaPert(4,7,12)
00120	Info/approval from client/architect	0		
00122	WALL TILING : SHOWER/TOILET AREAS	20	14%	BetaPert(3,6,10)
03200	SC: Finishings & decoration	0		
31	VINYL FLOORING	5	11%	BetaPert(4,7,12)
02100	Info/approval from client/architect	0		
00124	VINYL FLOORING	5	14%	BetaPert(3,6,10)
03300	SC: Finishings & decoration	0		
32	DRAINAGE WORKS	35	38%	BetaPert(4,11,22)
00126	Info from Client/Architect	0		
00128	DRAINAGE WORKS	35	23%	BetaPert(4,5,8)
00121	Delivery with insufficient quantity: Drainage	0	6%	BetaPert(2,3,4)
00400	Materials damaged on arrival: drainage	0	11%	BetaPert(1,3,6)
00129	Skill shortages: Labourers	0		
33	EDGE KERBING	10	11%	BetaPert(1,3,6)
00131	EDGE KERBING	10		
00132	Skill shortages: Labourers	0		
34	STONE UP & BITMAC FOOTPATHS	10	38%	BetaPert(4,11,22)
02500	Info from Client/Architect	0		
00134	STONE UP & BITMAC FOOTPATHS	10	11%	BetaPert(1,3,6)
00136	Skill shortages: Labourers	0		
35	LANDSCAPING	20	38%	BetaPert(4,11,22)
00137	Info from Client/Architect	0		
00138	LANDSCAPING	20	11%	BetaPert(1,3,6)
00139	Skill shortages: Labourers	0		
TOTAL#				

Created by: Jati Hatmoko
Report printed on: 08/Aug/07

MSP Risk Inputs
Page 1 of 1

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

(16) SO_All

Name	Description	Probability Task Exists	Duration Risk
1	START		
2	SITE ESTABLISHMENT/ FENCING (PRECAST)		
00004	SITE ESTABLISHMENT/ FENCING (PRECAS		
3	FORM ACCESS ROAD & REDUCE LEVEL		
00008	FORM ACCESS ROAD & REDUCE LEVEL		
0010	SC : Groundwork	8%	BetaPert(3,6,11)
4	CONSTRUCT FOUNDATIONS		
00013	CONSTRUCT FOUNDATIONS		
00014	SC: Foundation	6%	BetaPert(2,5,7)
5	ERECT STRUCTURAL STEEL FRAME		
00018	ERECT STRUCTURAL STEEL FRAME		
00020	SC: Steelwork	8%	BetaPert(3,6,14)
6	SUBSTRUCTURE BRICKWORK/BLOCKWORK		
00025	SUBSTRUCTURE BRICK/BLOCKWORK		
00026	SC: Bricks/blockwork	11%	BetaPert(4,7,12)
7	CONCRETE FLOOR SLAB		
00032	CONCRETE FLOOR SLAB		
00033	SC: Concrete floor	13%	BetaPert(1,6,12)
8	SUPERSTRUCTURE BRICK/BLOCKWORK		
00039	SUPERSTRUCTURE BRICK/BLOCKWORK		
00040	SC: Bricks/blockwork	11%	BetaPert(4,7,12)
9	INSULATION		
00045	INSULATION		
0080	SC: Bricks/blockwork	11%	BetaPert(4,7,12)
10	ROOF JOIST/FRAMEWORK		
00050	ROOF JOIST/FRAMEWORK		
00051	SC: Roofwork	16%	BetaPert(6,10,16)
11	ROOF COVERINGS		
00055	ROOF COVERINGS		
00056	SC: Roofwork	16%	BetaPert(6,10,16)
12	FASCIAS & SOFFITS		
00060	FASCIAS & SOFFITS		
00061	SC: Roofwork	16%	BetaPert(6,10,16)
13	WINDOWS & DOORS		
00069	WINDOWS & DOORS		
0020	SC: Windows & Doors	17%	BetaPert(4,10,18)
14	FLOOR SCREED		
00071	FLOOR SCREED		
0030	SC: Concrete floor	13%	BetaPert(1,6,12)
15	SUSPENDED CEILINGS GRID - TILES		
00074	SUSPENDED CEILINGS GRID - TILES		
0060	SC: Roofwork	16%	BetaPert(6,10,16)
16	FLOOR TILING		
00078	FLOOR TILING		
0040	SC: Finishings & Decoration	14%	BetaPert(3,6,10)
17	PARTITIONS		
00080	PARTITIONS		
0130	SC: Finishings & Decoration	14%	BetaPert(3,6,10)
18	PLASTERWORK		
00083	PLASTERWORK		
00084	SC: Plasterworks	26%	BetaPert(6,11,18)
19	JOINERY WORKS		
00088	JOINERY WORKS		
0090	SC: Finishings & Decoration	14%	BetaPert(3,6,10)
20	M & E INSTALLATIONS		
00091	M & E INSTALLATIONS		
00092	SC: M&E	12%	BetaPert(4,7,13)
21	2nd FIX ELECTRICAL		
00094	2nd FIX ELECTRICAL		
00095	SC: M&E	12%	BetaPert(4,7,13)
22	DECORATION		
00098	DECORATION		
0050	SC: Finishings & decoration	14%	BetaPert(3,6,10)
23	FURNISHING		
00102	FURNISHING		
0100	SC: Finishings & decoration	14%	BetaPert(3,6,10)
24	FIXTURES & FITTINGS		
00106	FIXTURES & FITTINGS		
0110	SC: Finishings & decoration	14%	BetaPert(3,6,10)
25	TEST & COMMISSION		
00109	TEST & COMMISSION		
26	FINISH		
27	IPS FRAMEWORK/PANELING/VANITY UNITS		
00112	IPS FRAMEWORK/PANELING/VANITY UNITS		
00113	Skill shortages: Plumbers	28%	BetaPert(4,8,13)
28	PLUMBING/SANITARYWARE		
00115	PLUMBING/SANITARYWARE		
00116	Skill shortages: Plumbers	28%	BetaPert(4,8,13)
29	SHOWER CUBICLES		
00118	SHOWER CUBICLES		
0070	Materials damaged on arrival: Shower cubicles	5%	BetaPert(6,10,15)
30	WALL TILING - SHOWER/TOILET AREAS		
00122	WALL TILING - SHOWER/TOILET AREAS		
0120	SC: Finishings & decoration	14%	BetaPert(3,6,10)
31	VINYL FLOORING		
00124	VINYL FLOORING		
0140	SC: Finishings & decoration	14%	BetaPert(3,6,10)
32	DRAINAGE WORKS		
00128	DRAINAGE WORKS		
00129	SC: Drainage works	4%	BetaPert(2,4,8)
33	EDGE KERBING		
00131	EDGE KERBING		
00132	Skill shortages: Labourers	11%	BetaPert(1,3,6)
34	STONE UP & BITMAC FOOTPATHS		
00134	STONE UP & BITMAC FOOTPATHS		
00135	SC: Groundwork	8%	BetaPert(3,6,11)
35	LANDSCAPING		
00138	LANDSCAPING		
00139	SC: Groundwork	8%	BetaPert(3,6,11)
TOTALS			

Created by: Jati Hatmoko
Report printed on: 08/Aug/07

MSP Risk Inputs
Page 1 of 1

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

This copy of Pertmaster is for educational purposes only and is not licenced for commercial use.

Appendix C1

Various paths trough the CPM network, Total floats and potential delays

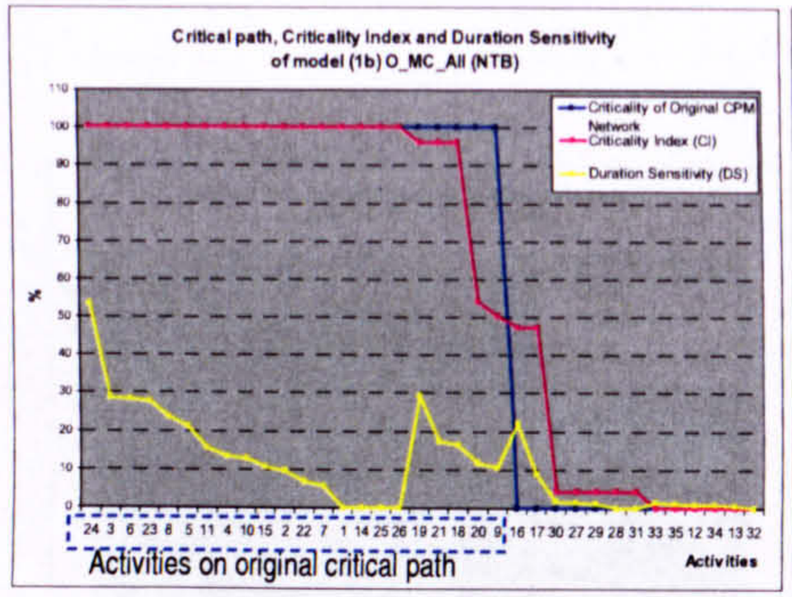
Paths	Activities	Total Float (TF) (days)	Activities which share the total float	Total max delay duration (in days) that can potentially impact on activities in column (d)																			
				(1b) O_MC_All (NTB)	(2) MC_info	(3) O/P_MC_mat	(4) MC_plant	(5) MC_lab	(6) MC_mat_late (TB/NTB)	(7) MC_mat_wro	(8) MC_mat_dmg	(9) MC_mat_ins	(10) MC_mat_diff	(11b) SS_work_all (NTB)	(12) O/P_SS_work_sub (TB/NTB)	(13) O/P_SS_work_sup (TB)	(14) O/P_SS_work_M&E (TB/NTB)	(15) O/P_SS_work_fin (TB/NTB)	(16) SO_All	(17) SO_work_sub	(18) SO_work_sup	(19) SO_work_M&E	(20) SO_work_fin
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)	(s)	(t)	(u)	(v)	(w)	(x)
1	1*-2-3-4-5-6-7-8-10-11-12-13-18-19-21-22-23-24-25-26*	46	12, 13	125	**11**	96	**11**	**7**	**13**	48	**27**	**8**	**0**	**45**	125	102	125	125	**34**	**0**	**16**	**0**	**18**
2	1*-2-3-4-5-6-7-8-10-11-14-15-16-17-18-19-21-22-23-24-25-26*	5	16, 17	71	24	36	**0**	11	**0**	**0**	**0**	**0**	36	44	71	71	71	44	20	**0**	**0**	**0**	20
3	**1*-2-3-4-5-6-7-8-10-11-14-15-20-18-19-21-22-23-24-25-26***	**0**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	1*-2-3-4-5-6-7-8-10-11-14-15-27-28-29-30-31-22-23-24-25-26*	17	27,28,29,30,31	101	24	51	**0**	26	**0**	**0**	**15**	**0**	36	85	101	101	101	85	20	**0**	**0**	**0**	20
5	1*-2-3-4-5-6-7-8-9-10-11-12-13-18-19-21-22-23-24-25-26*	46	12, 13	125	**11**	96	**11**	**7**	**13**	48	**27**	**8**	**0**	**45**	125	102	125	125	**34**	**0**	**16**	**0**	**18**

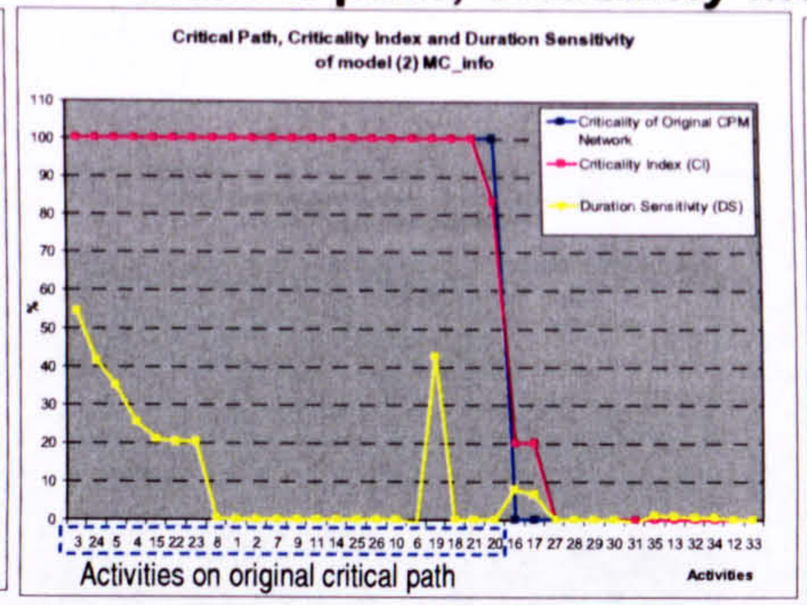
Note: The bold and underlined figures in columns (e) to (x) indicate total maximum delay durations which will never exceed the Total Float (TF) available on each path; hence the paths will never be critical. For example, the total maximum delay duration on path 1 of model (2)MC_info (column f) is 11 days, which is less than the Total float available of 46 days, hence path 1 of this model will never be critical.

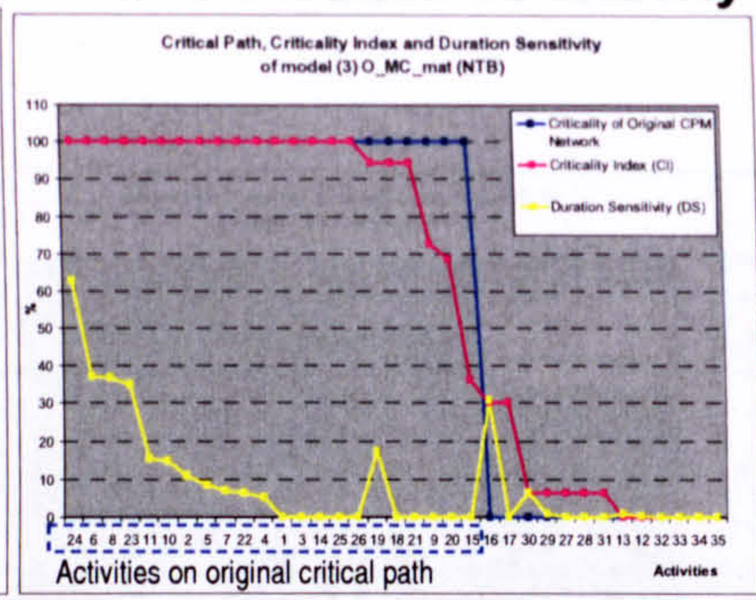
Appendix C1 (Continued)

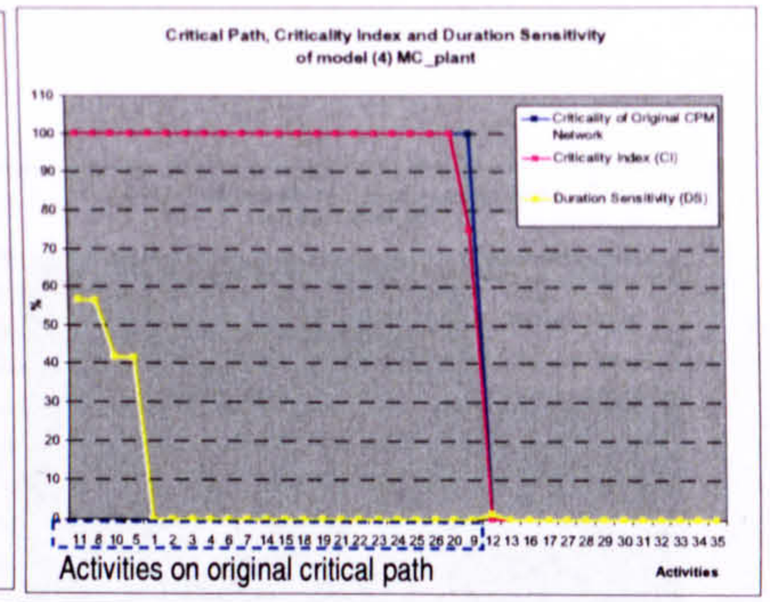
Paths	Activities	Total Float (TF) (days)	Activities which share the total float	Total max delay duration (in days) that can potentially impact on activities in column (d)																		
				(1b) O_MC_All (NTB)	(2) MC_info	(3) O/P_MC_mat	(4) MC_plant	(5) MC_lab	(6) MC_mat_late (TB/NTB)	(7) MC_mat_wro	(8) MC_mat_dmg	(9) MC_mat_ins	(10) MC_mat_diff	(11b) SS_work_all (NTB)	(12) O/P_SS_work_sub (TB/NTB)	(13) O/P_SS_work_sup (TB)	(14) O/P_SS_work_M&E (TB/NTB)	(15) O/P_SS_work_fin (TB/NTB)	(16) SO_All	(17) SO_work_sub	(18) SO_work_sup	(19) SO_work_M&E	(20) SO_work_fin
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)	(s)	(t)	(u)	(v)	(w)	(x)
6	1*-2-3-4-5-6-7-8-9-10-11-14-15-16-17-18-19-21-22-23-24-25-26*	5	16, 17	71	24	36	0	11	0	0	0	0	36	44	71	71	71	44	20	0	0	0	20
7	**1*-2-3-4-5-6-7-8-9-10-11-14-15-20-18-19-21-22-23-24-25-26***	**0**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	1*-2-3-4-5-6-7-8-9-10-11-14-15-27-28-29-30-31-22-23-24-25-26*	17	27,28,29,30,31	101	24	51	0	26	0	0	15	0	36	85	101	101	101	85	20	0	0	0	20
9	1*-2-3-32-33-34-35-25-26*	185	32,33,34,35	102	66	12	0	24	0	0	4	8	0	102	102	102	102	102	30	30	0	0	0

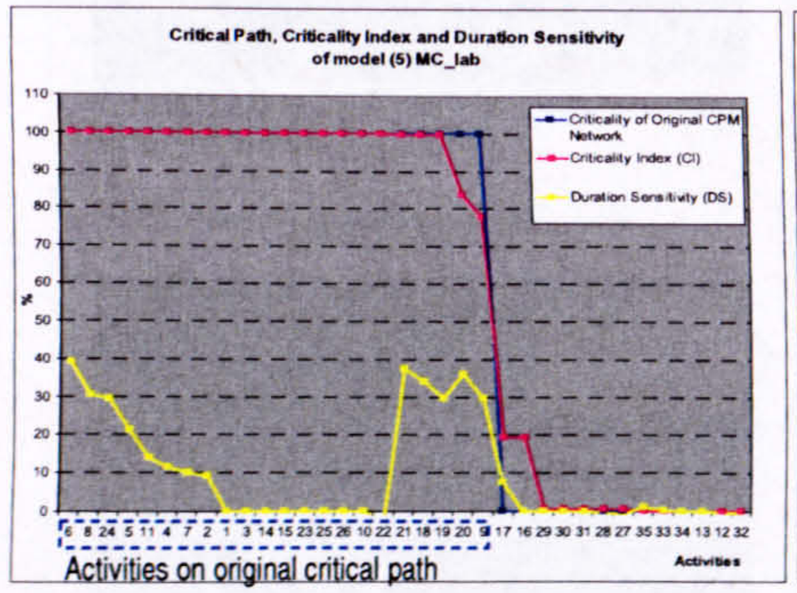
Appendix C2
Critical path, Criticality index and Duration sensitivity

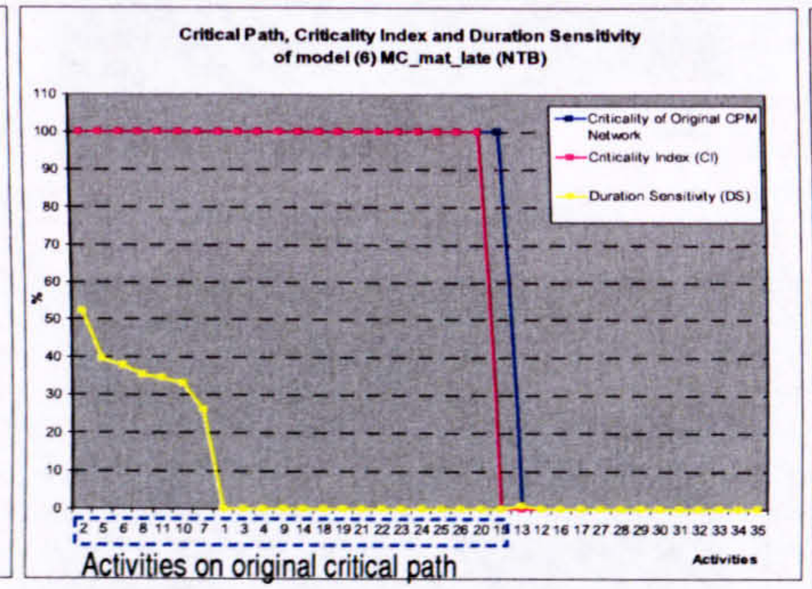


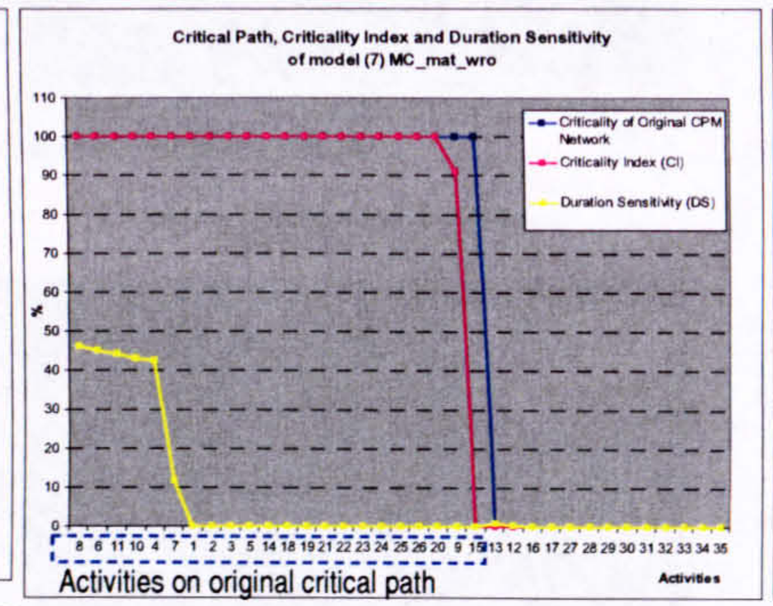


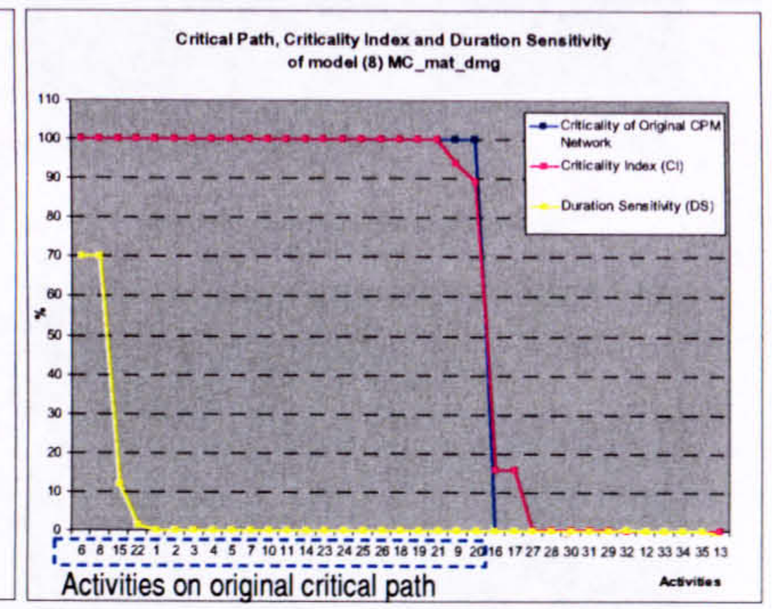


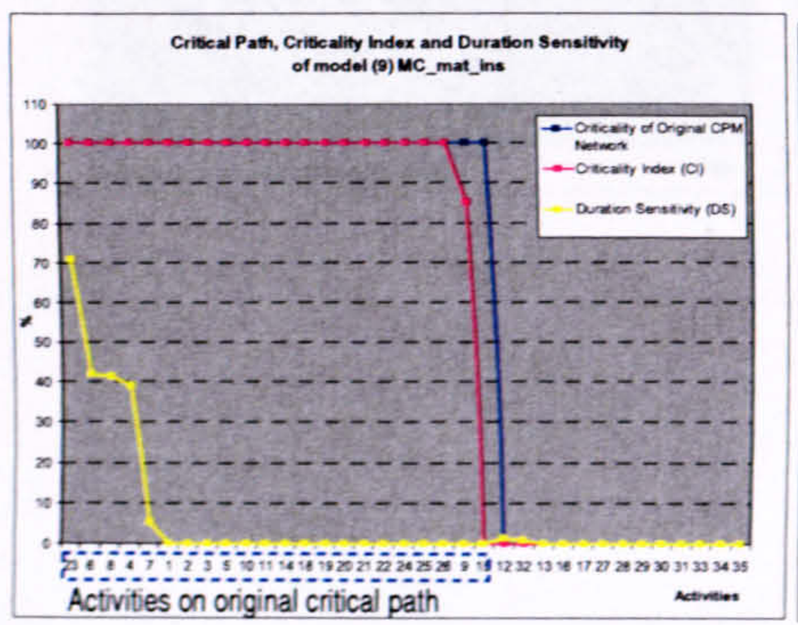


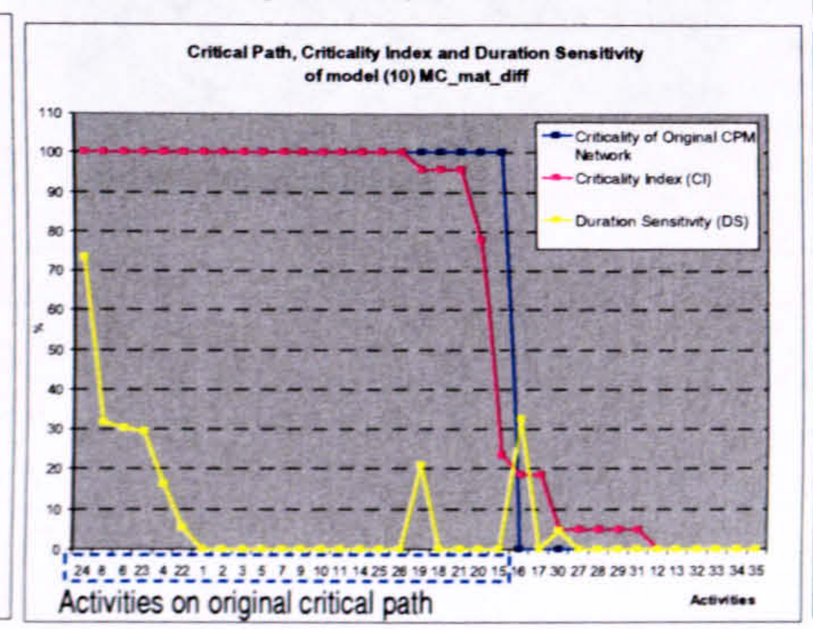


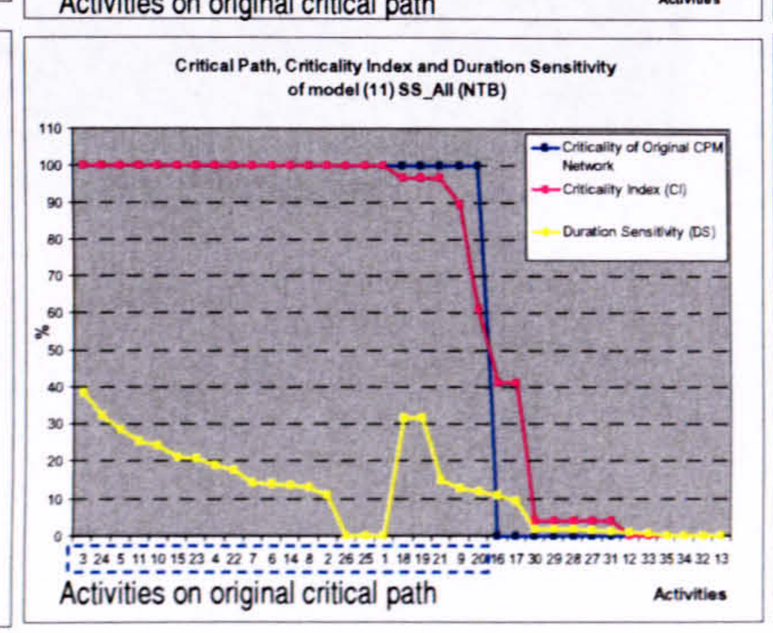


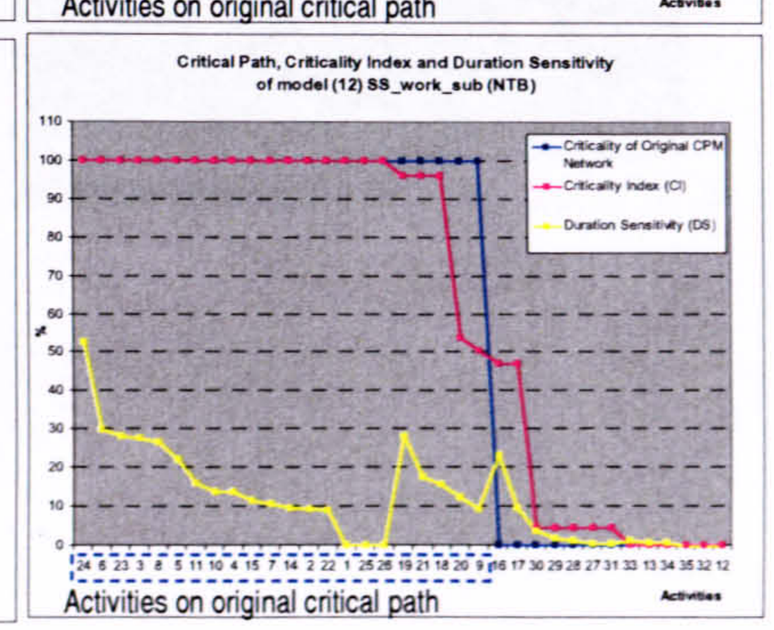




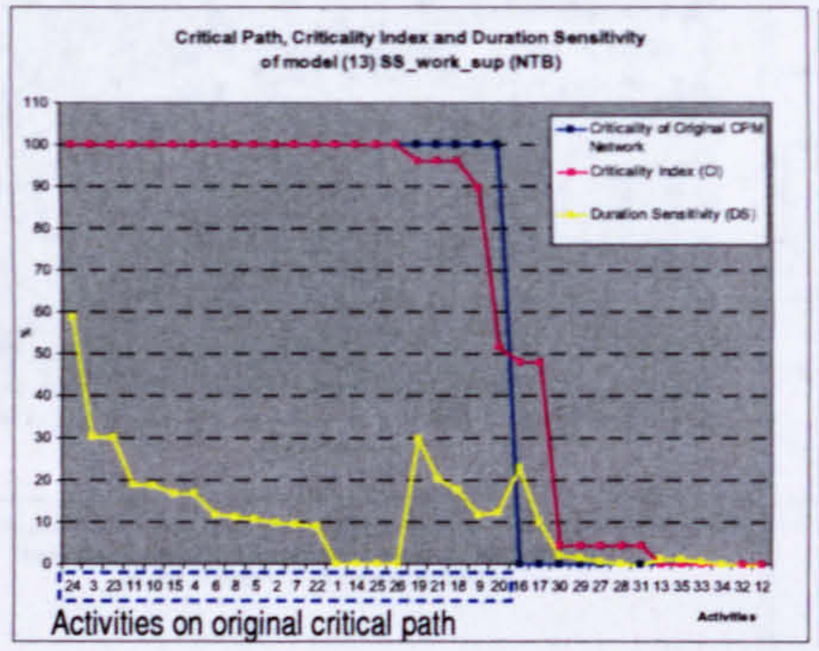


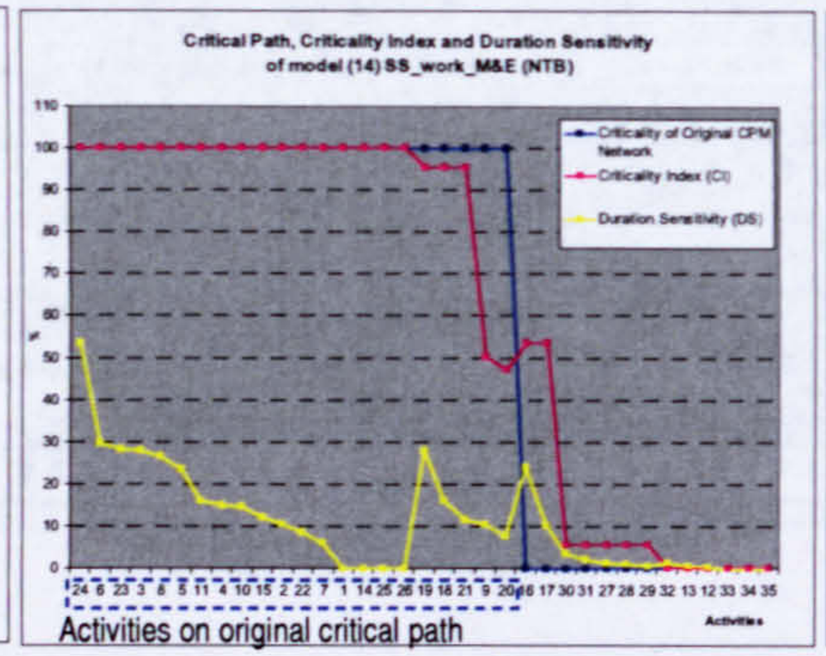


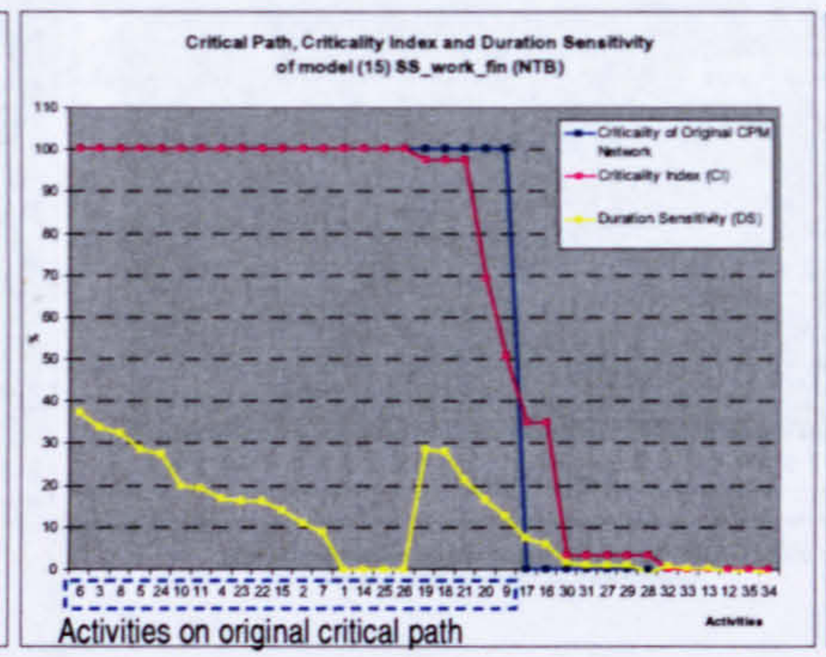


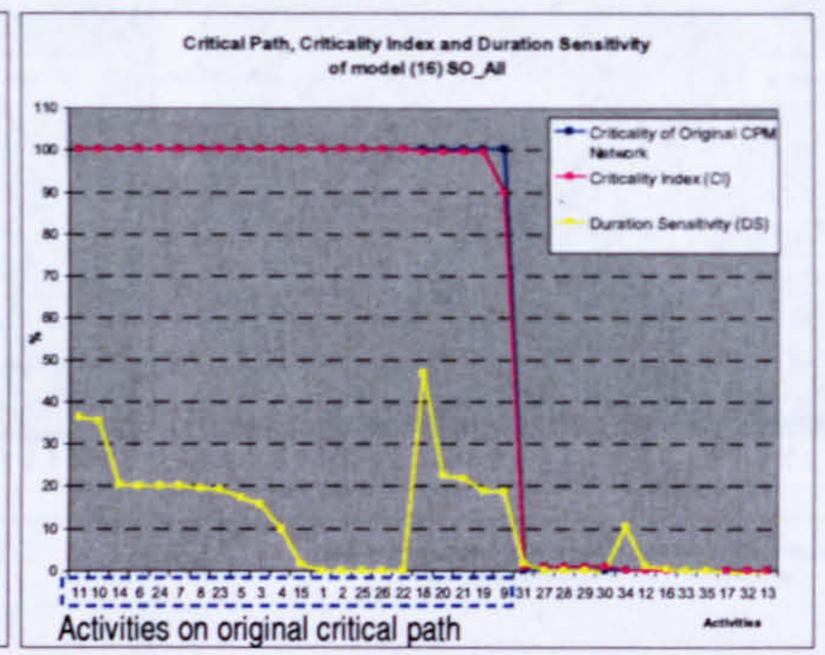


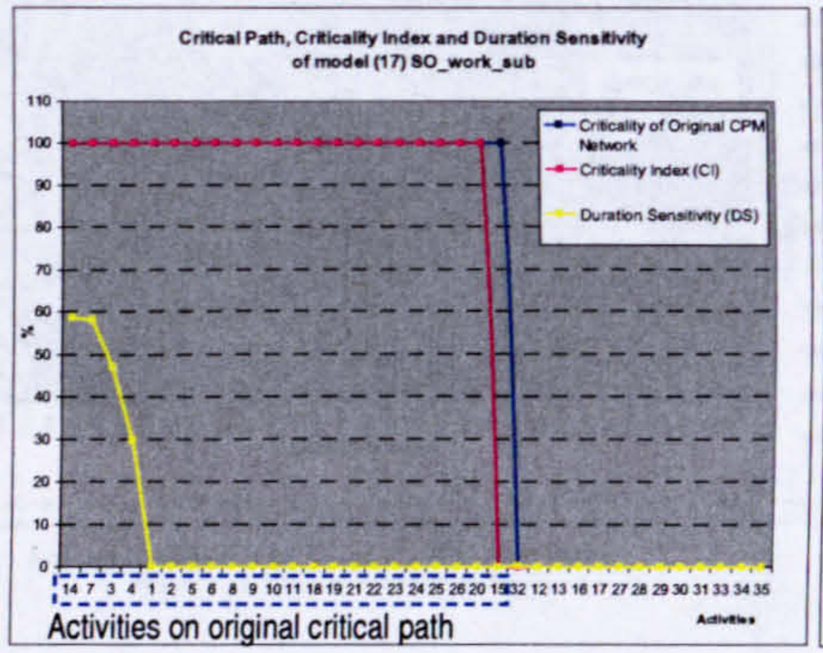
Appendix C2 (Continued)
Critical path, Criticality index and Duration sensitivity

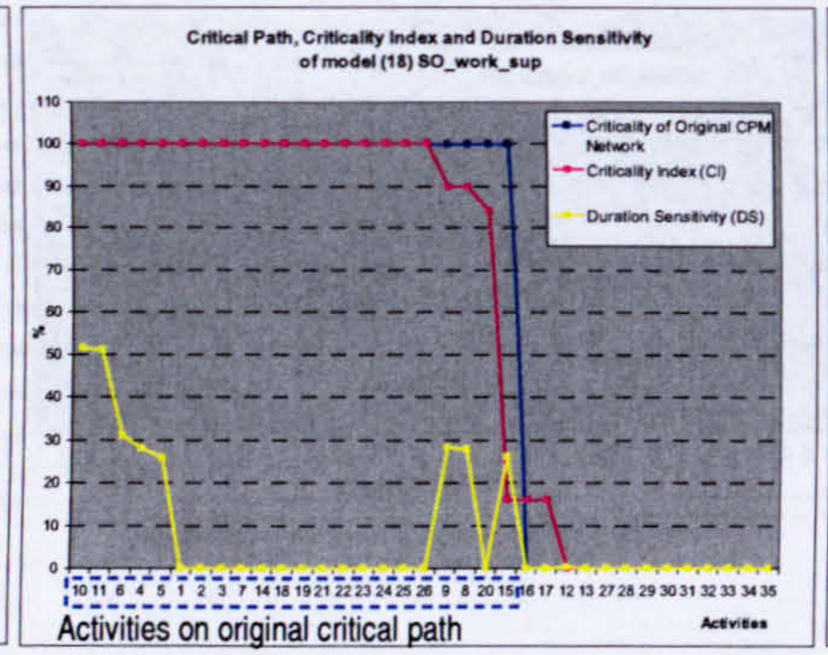


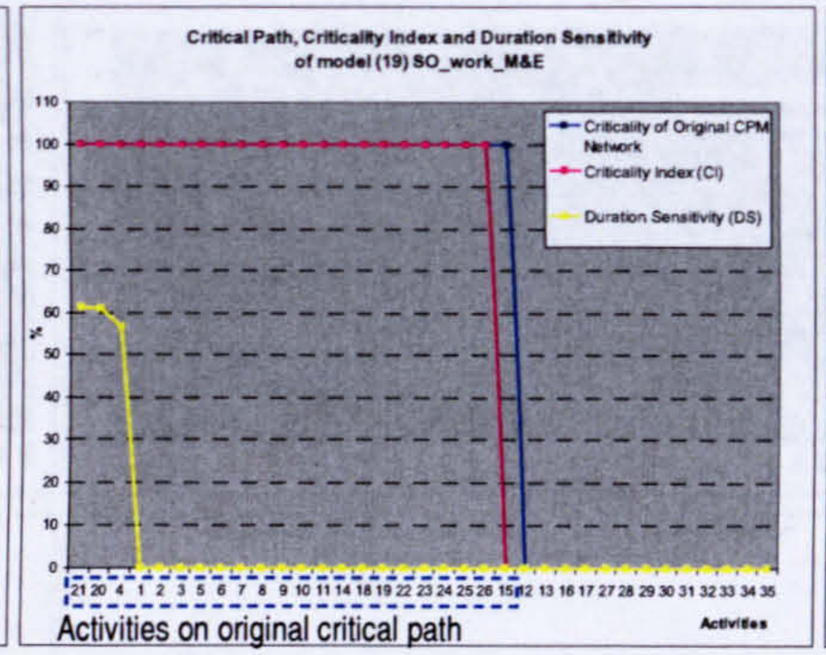


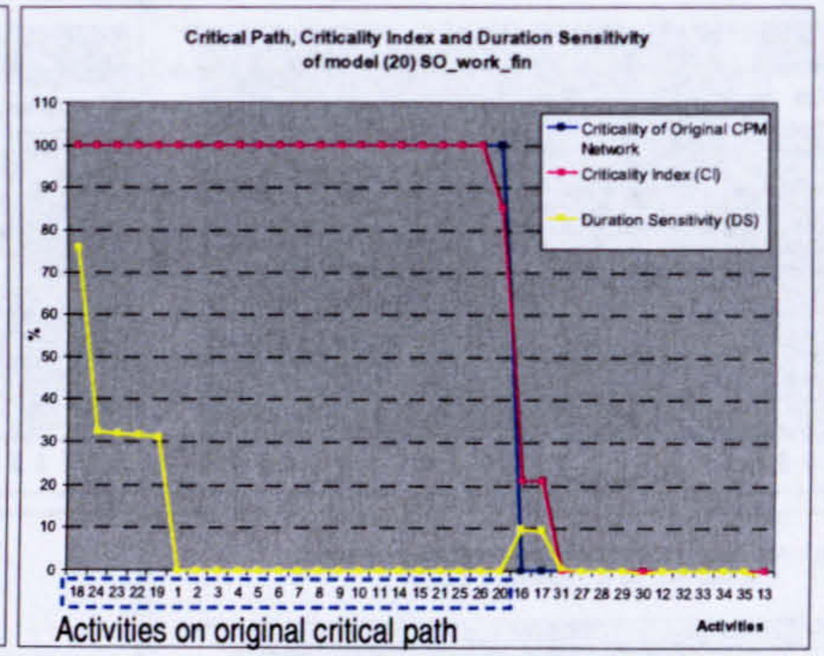




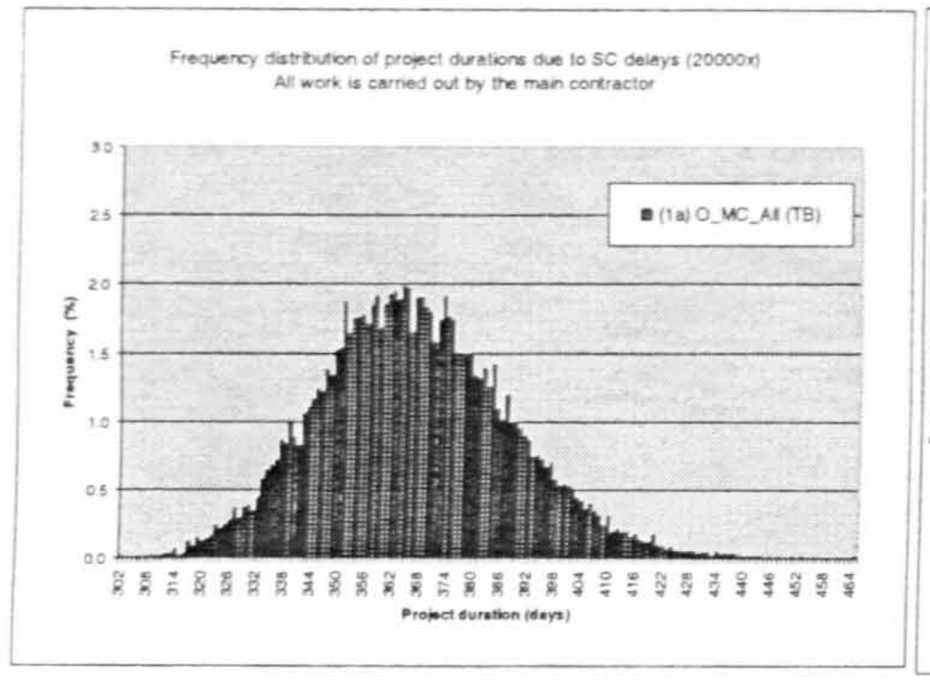


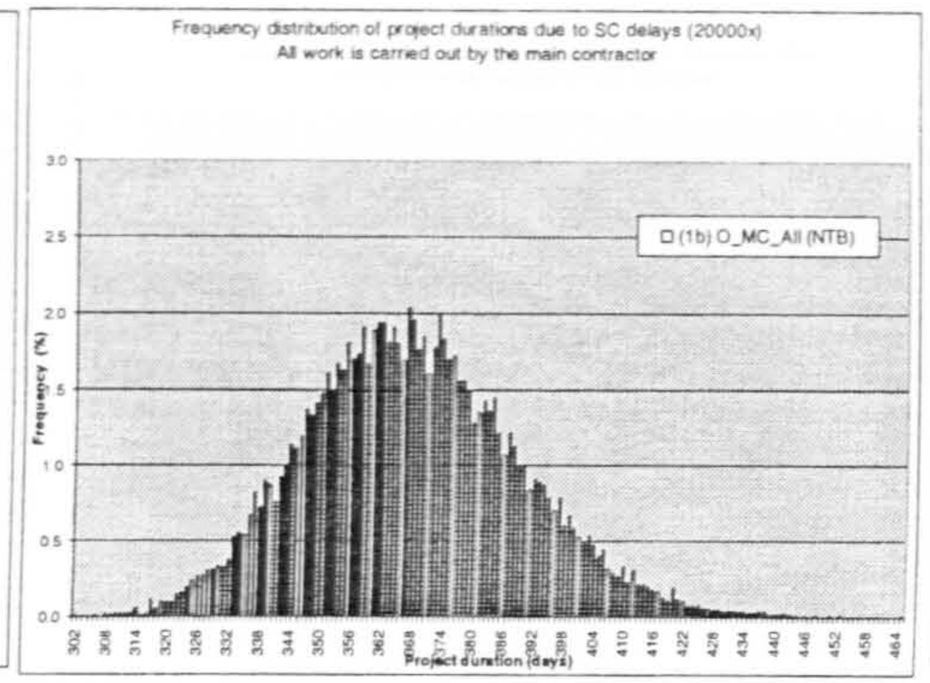


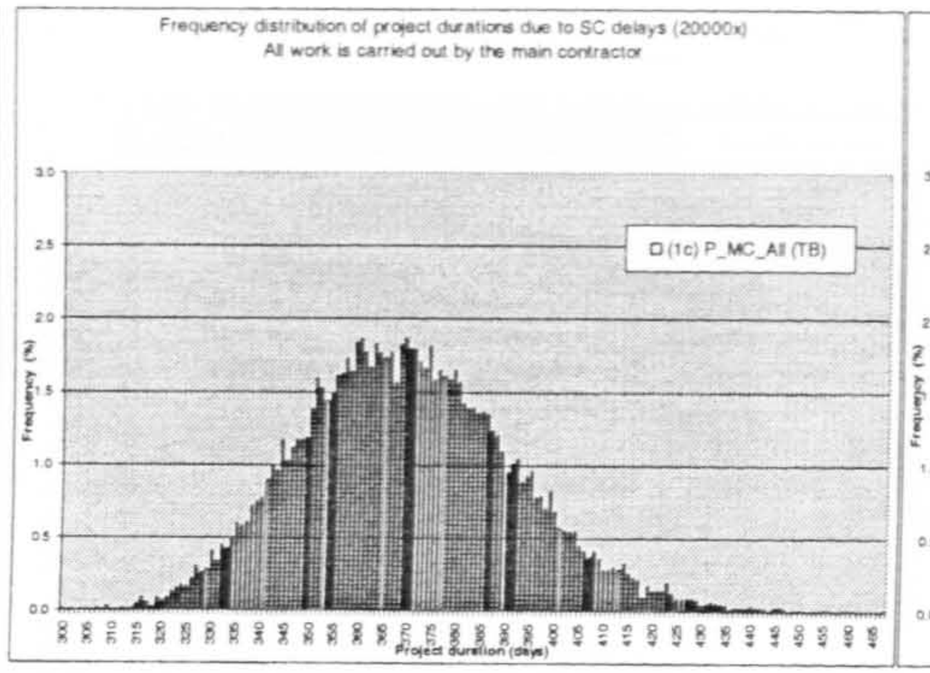


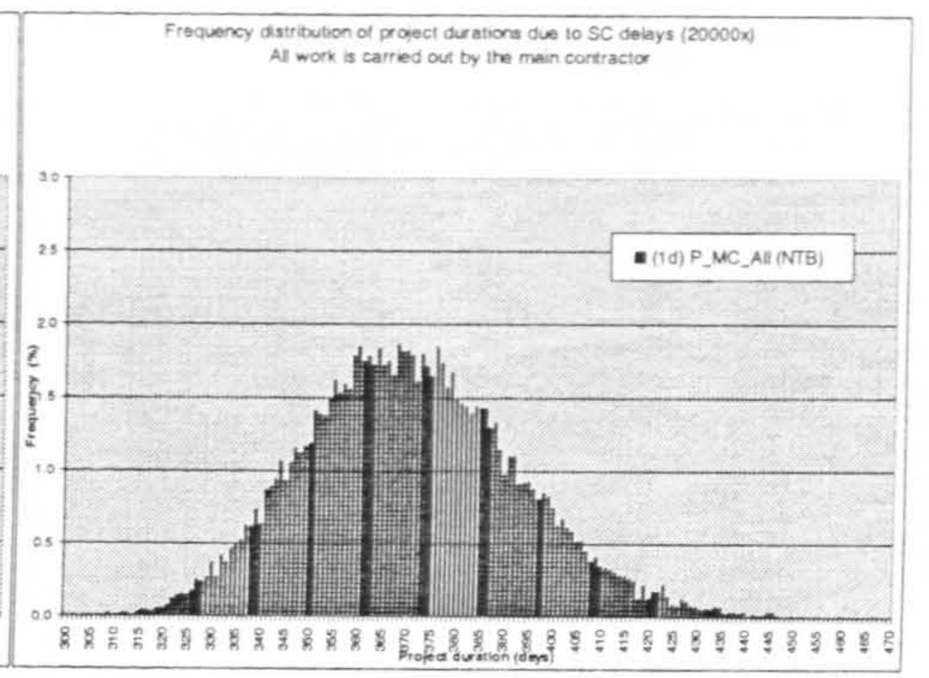


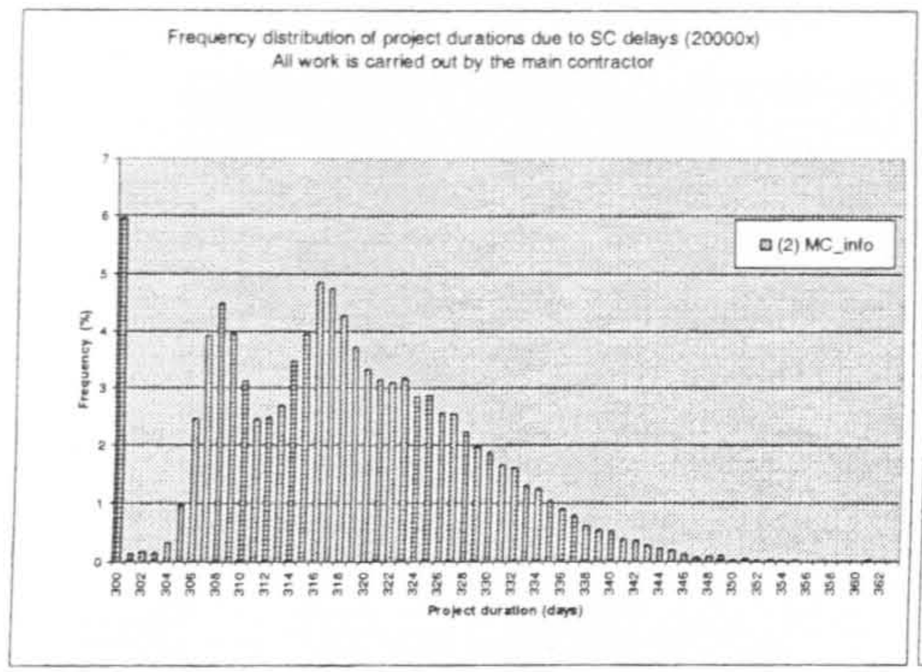
Appendix C3 - Histogram results

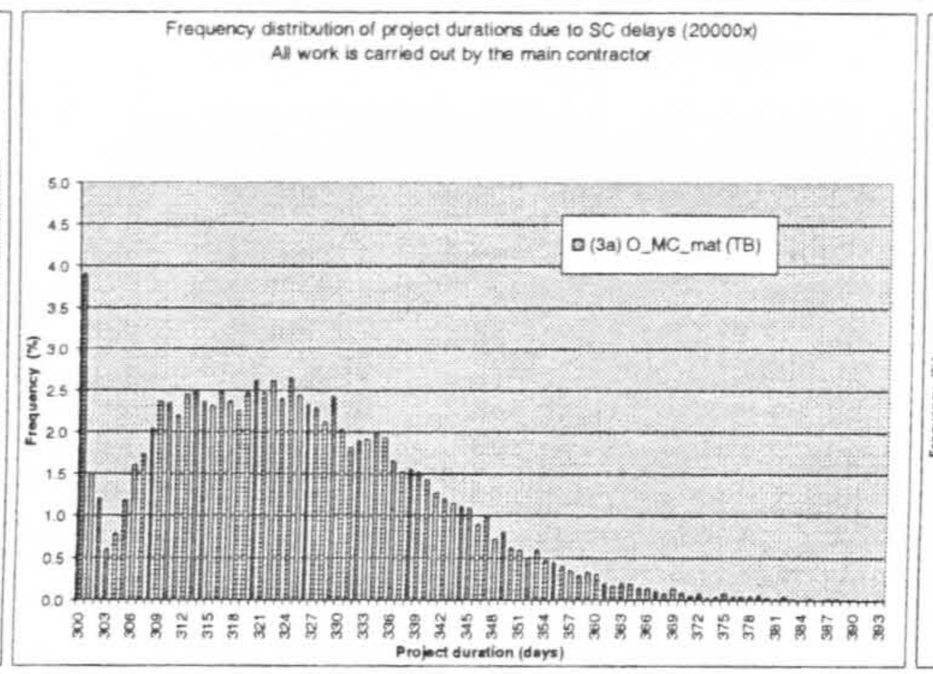


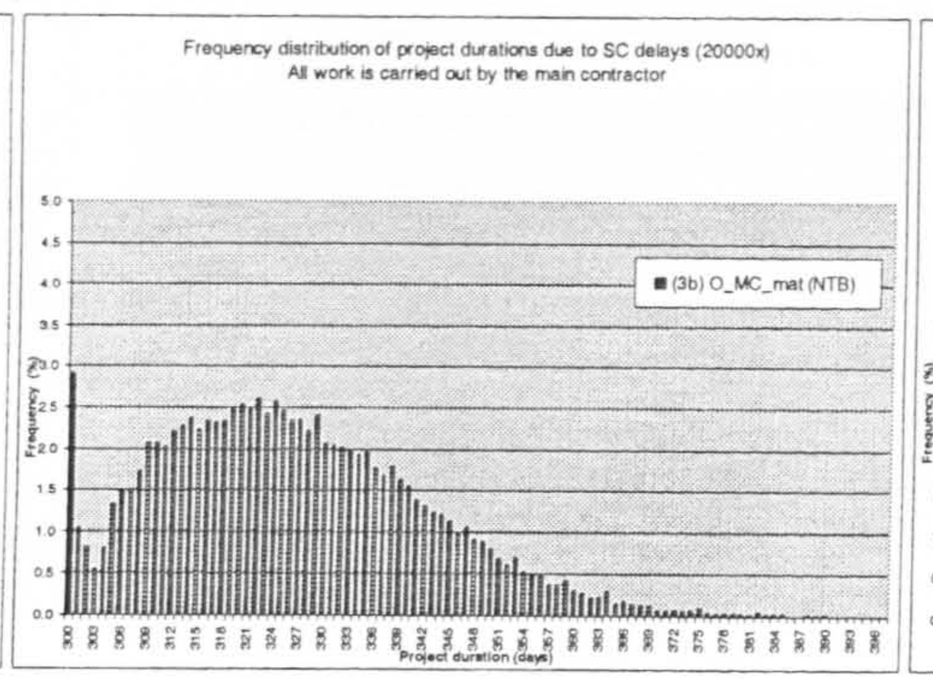


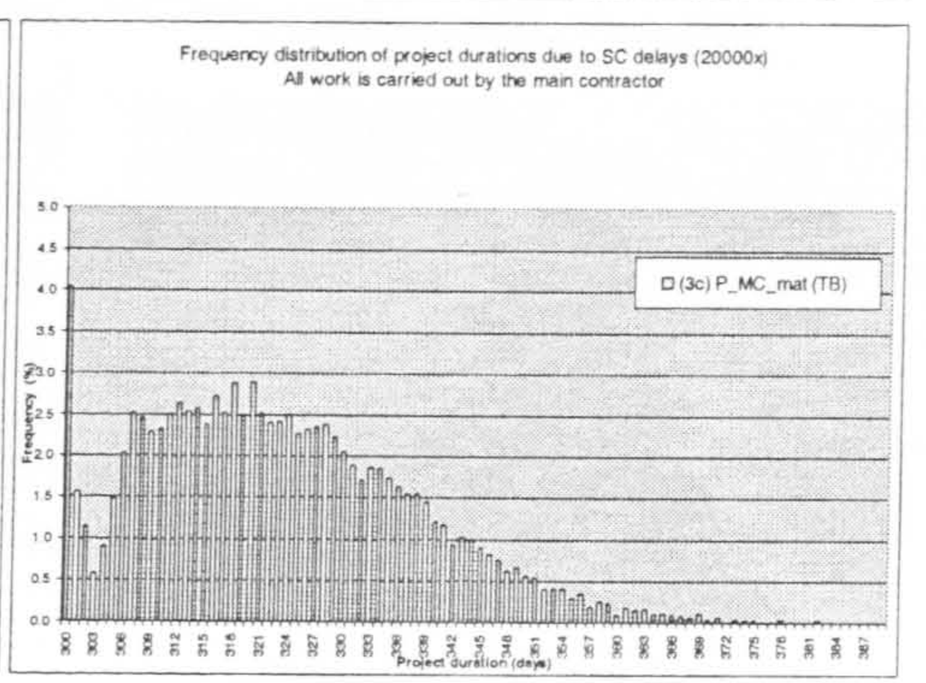


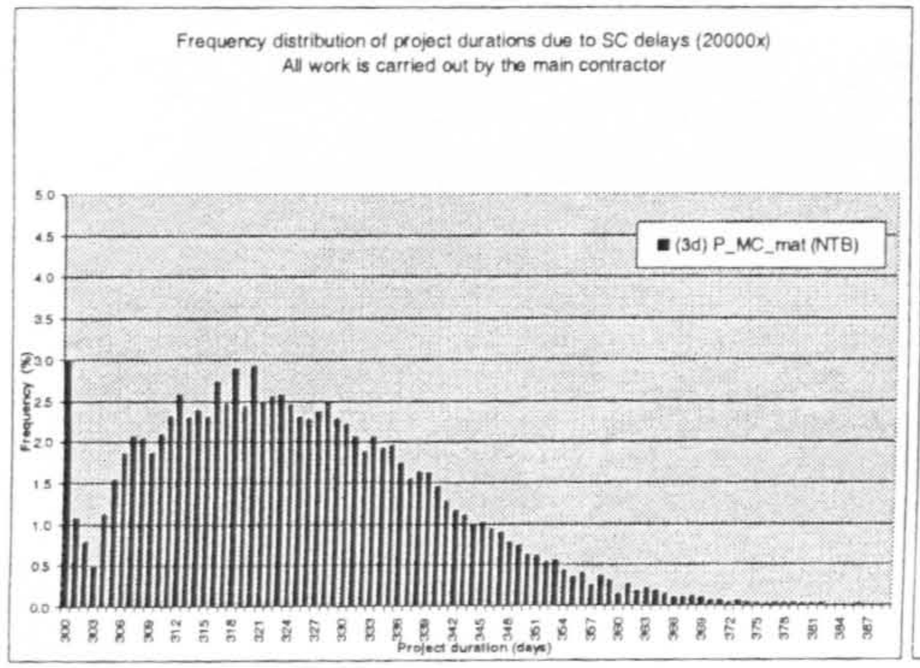


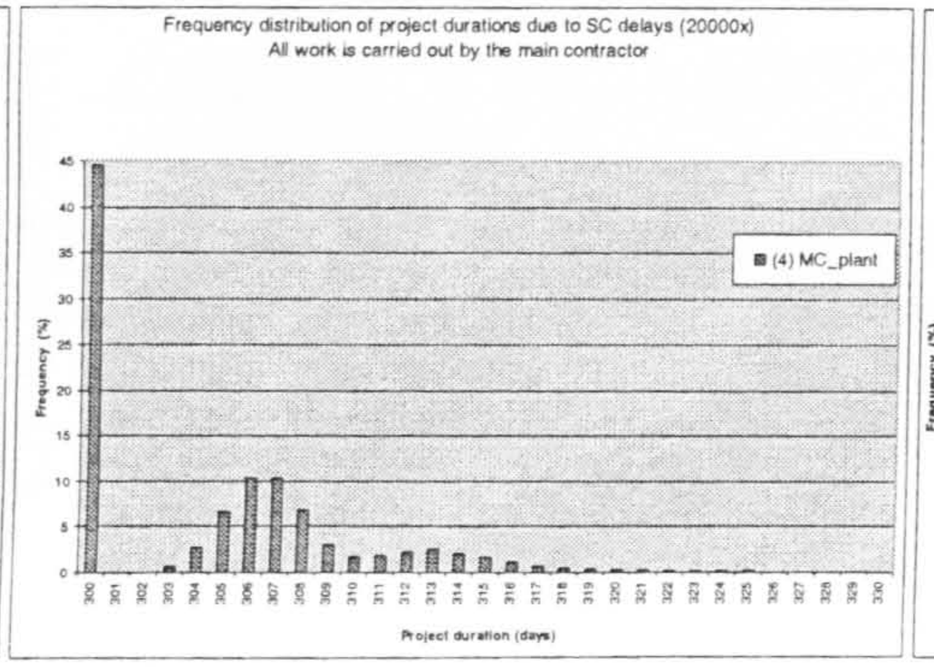


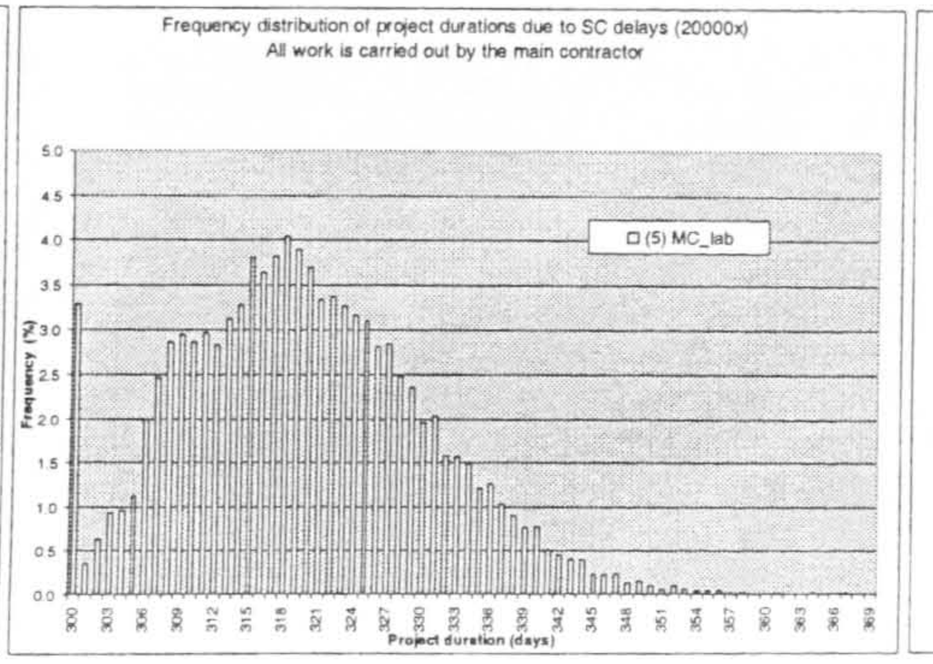


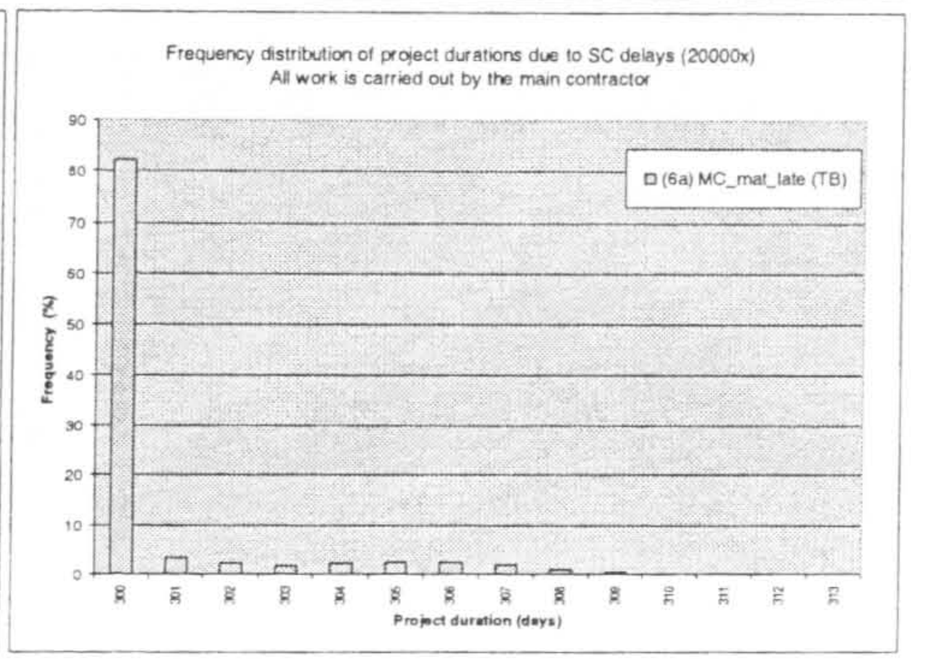




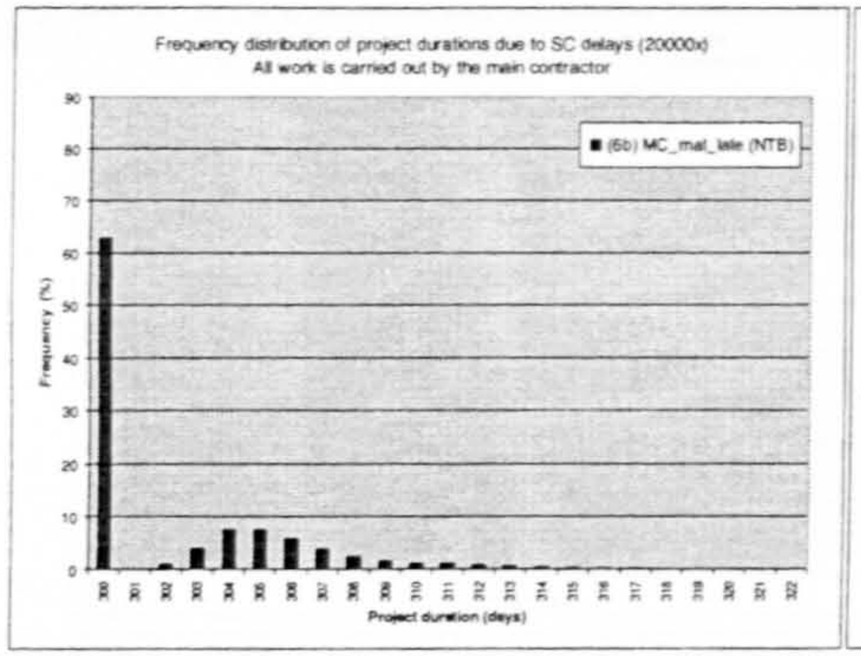


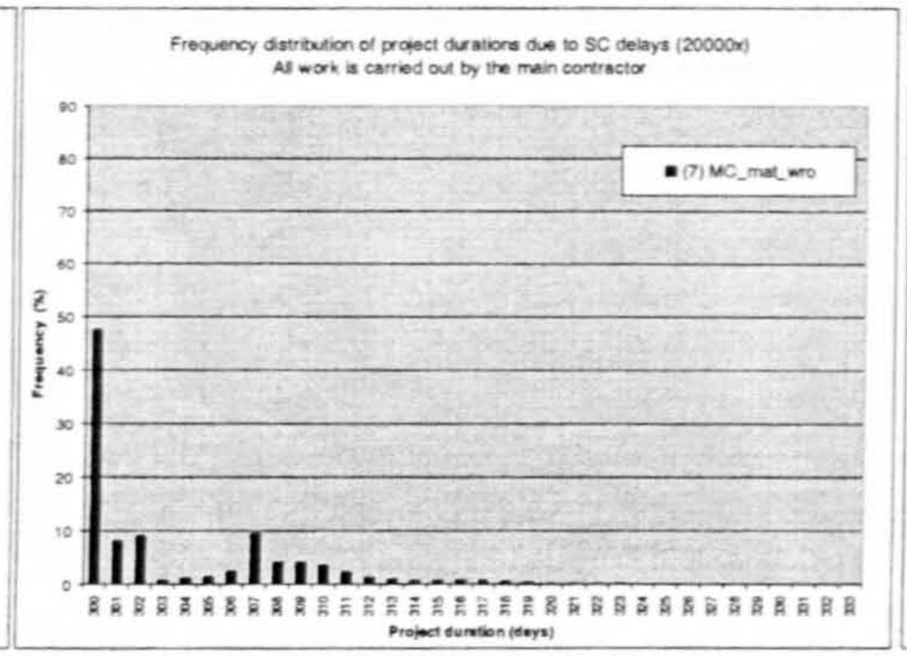


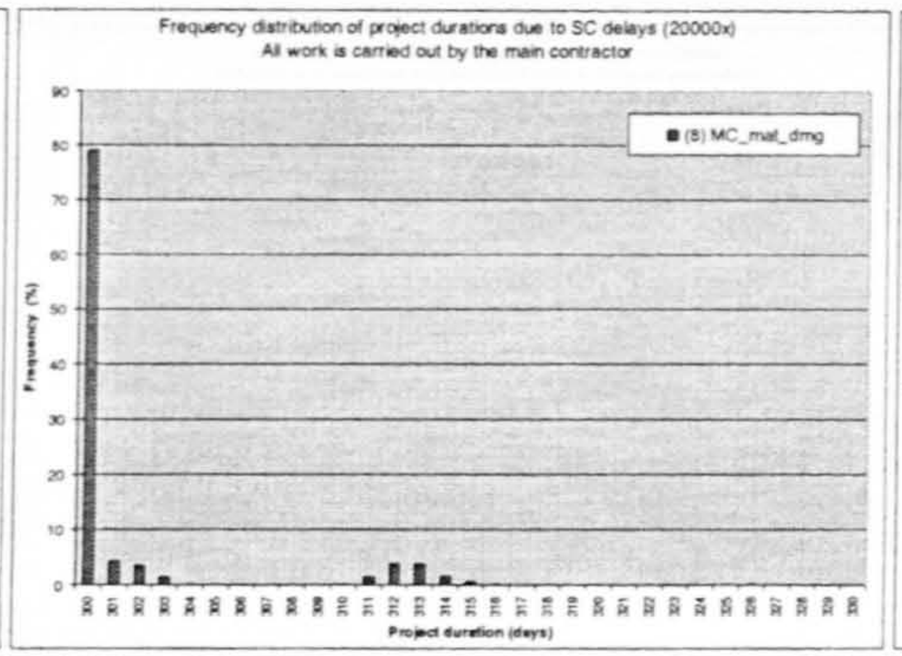


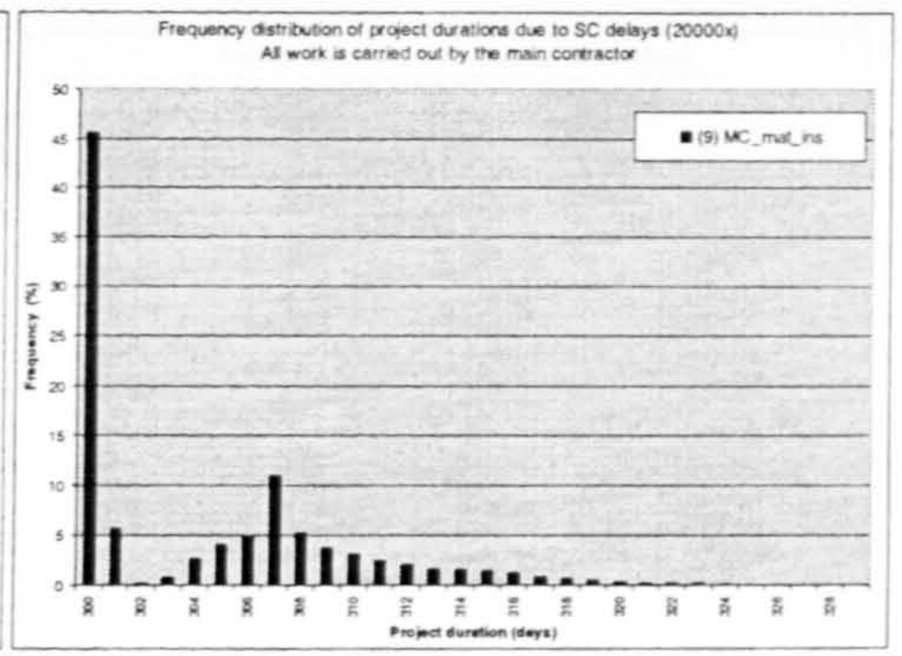


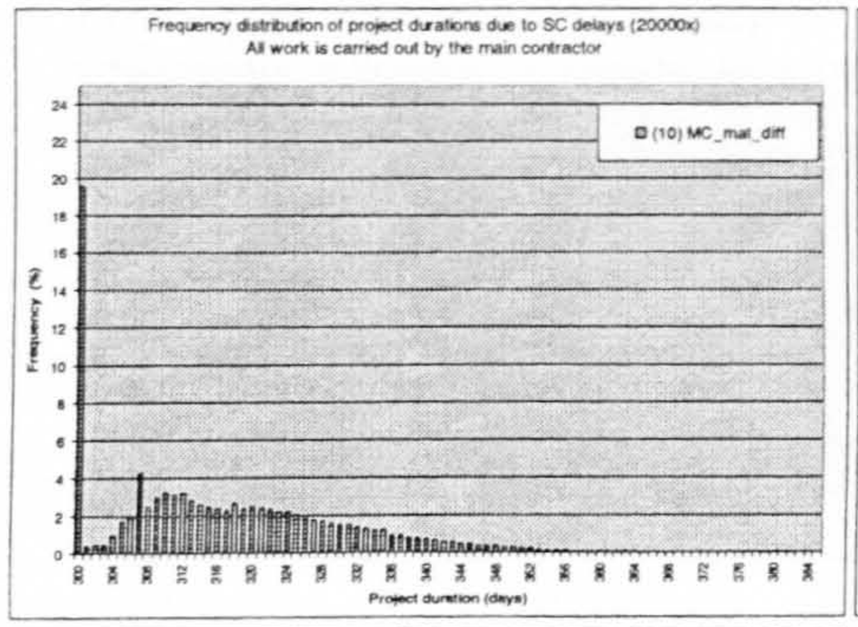
Appendix C3 - Histogram results (continued)

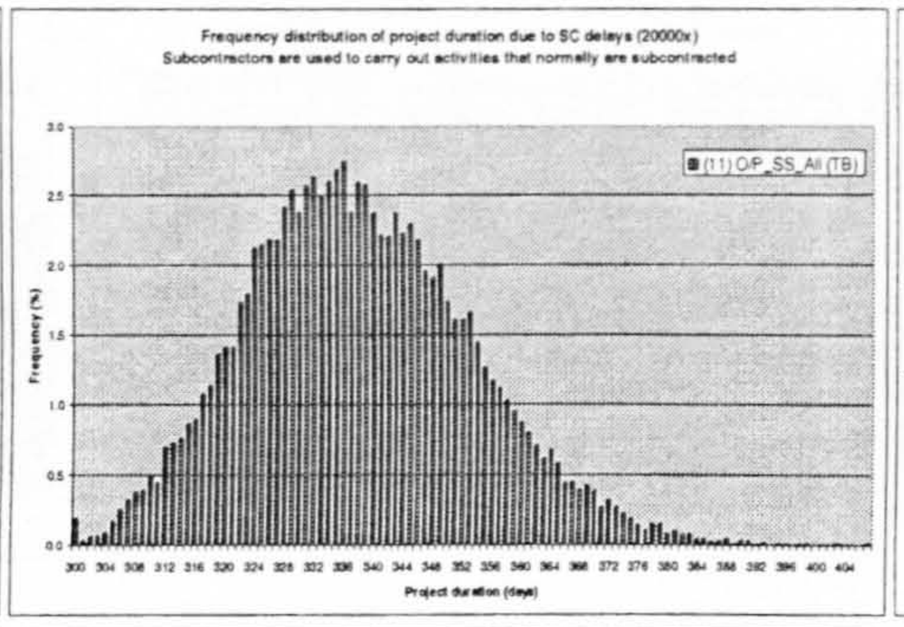


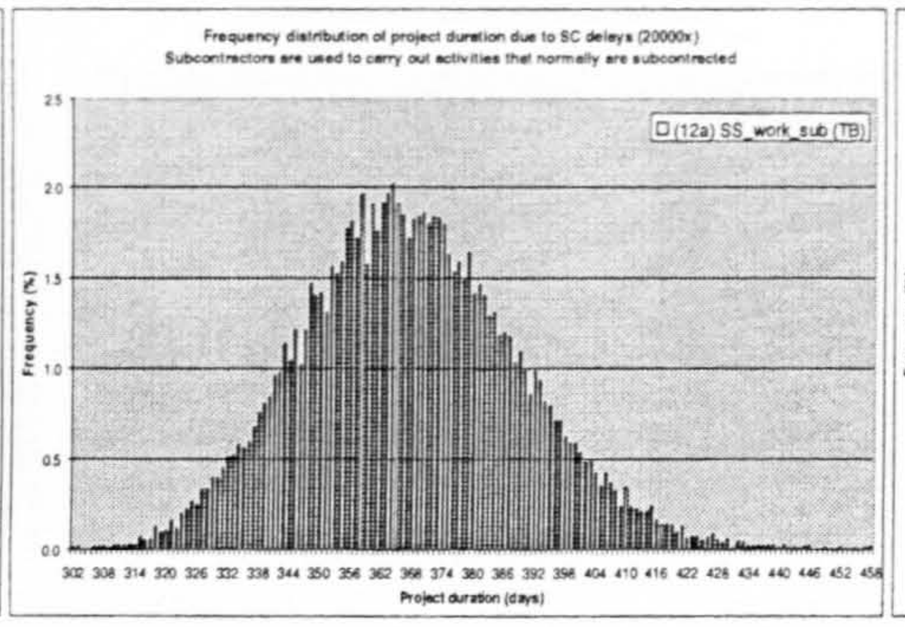


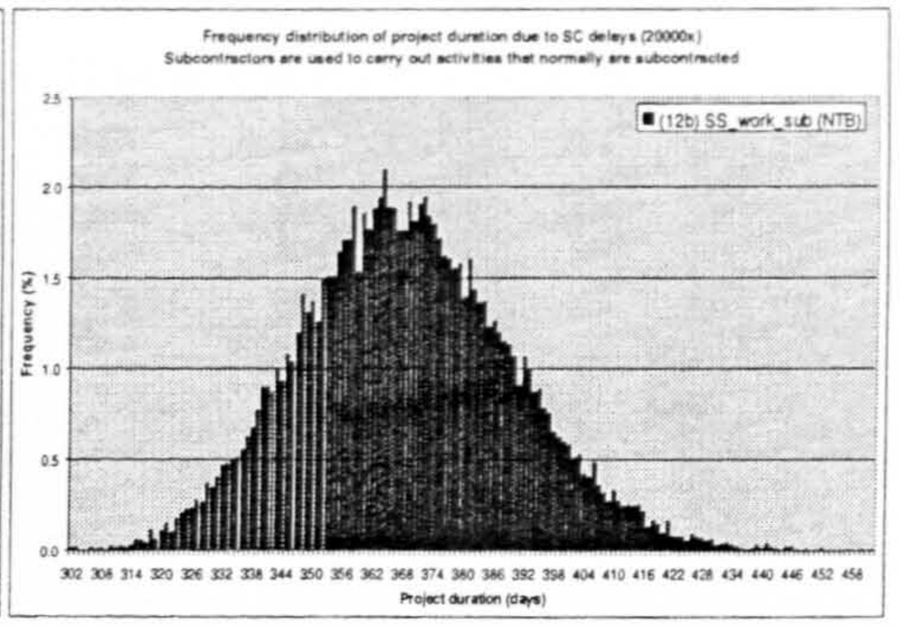


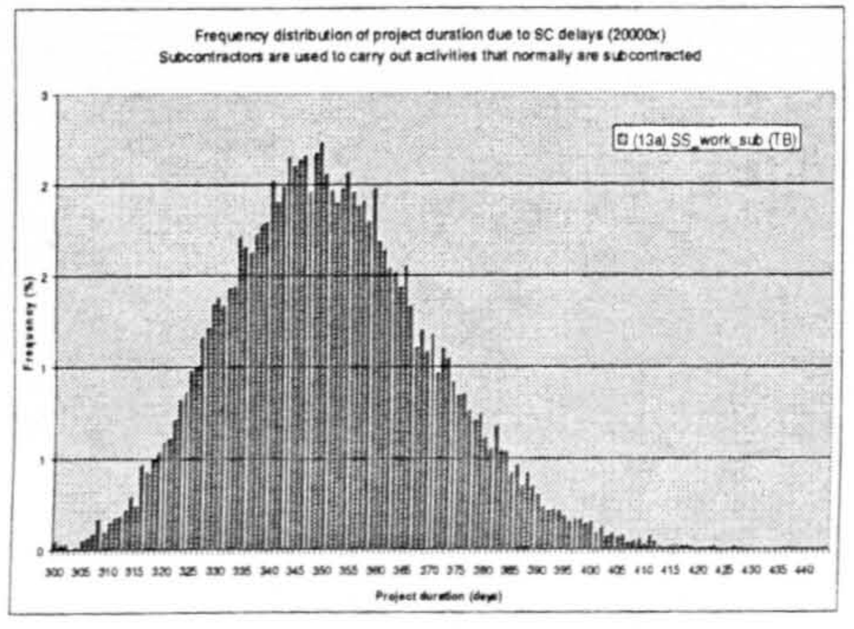


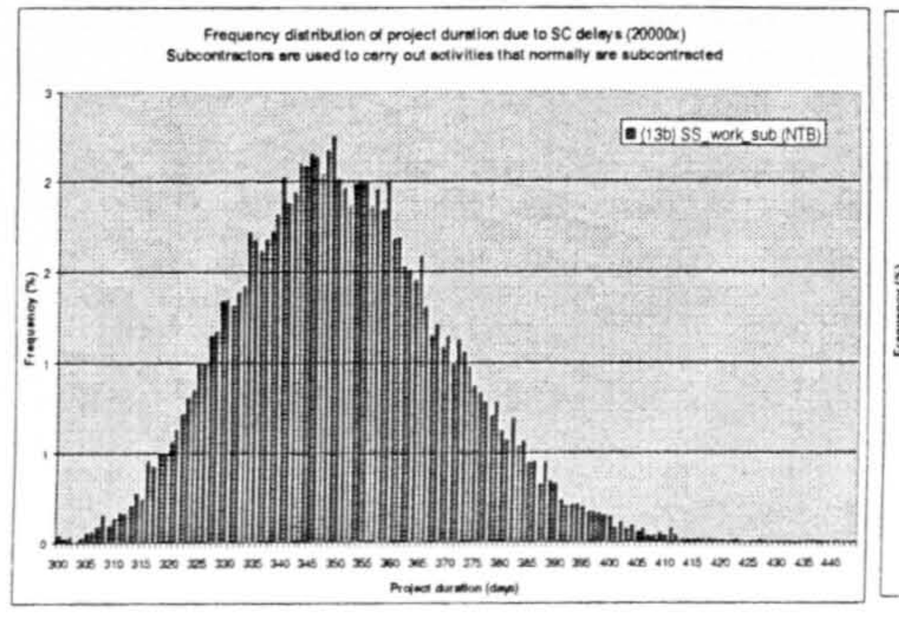


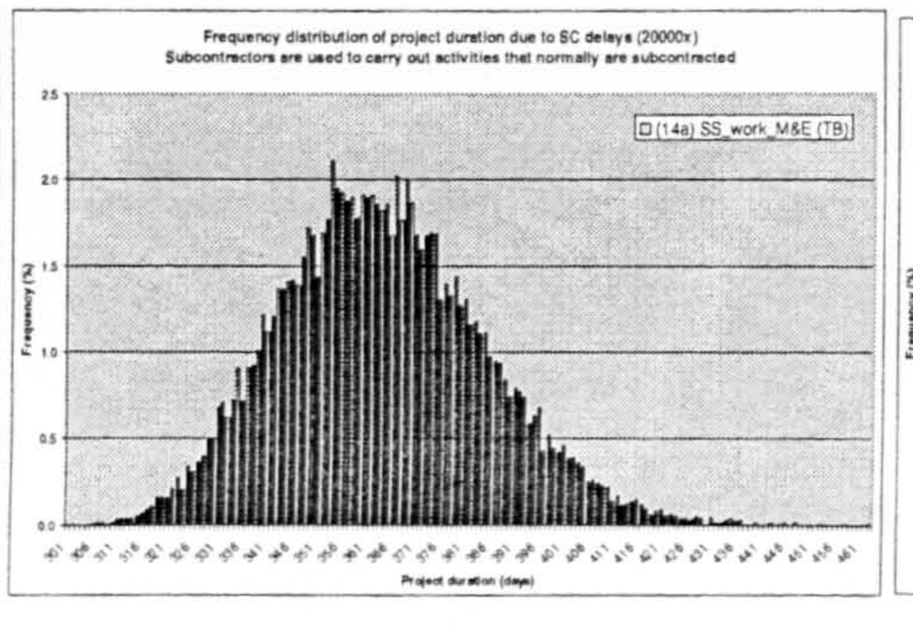


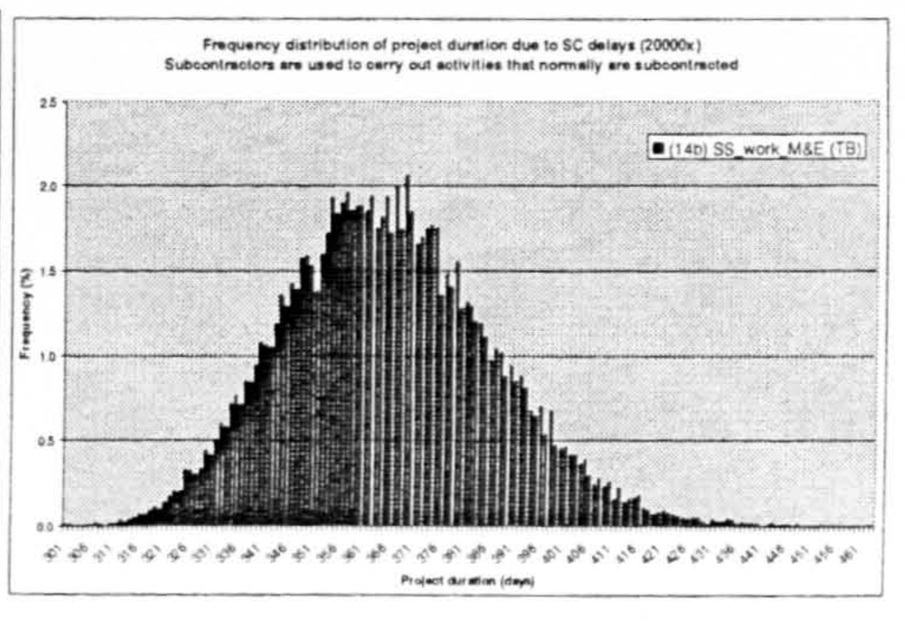




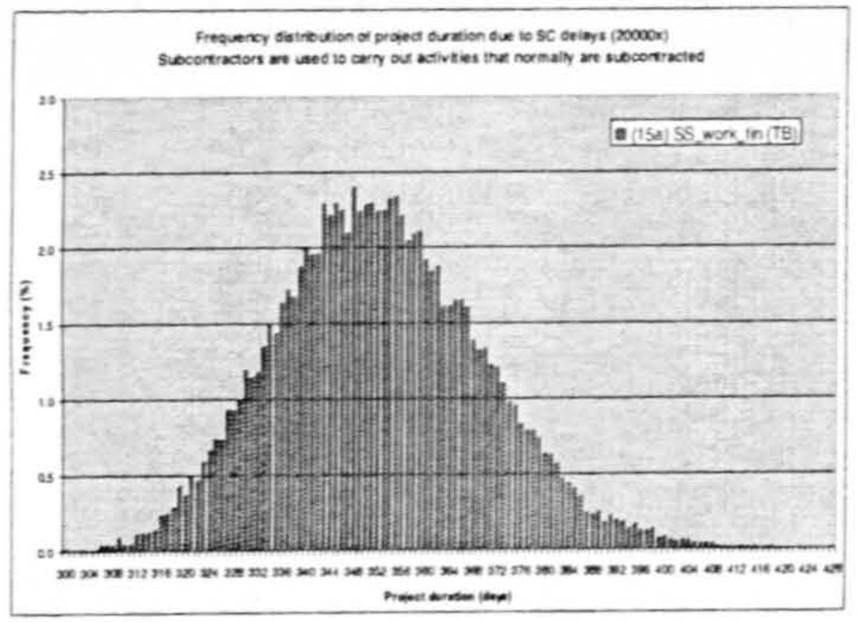


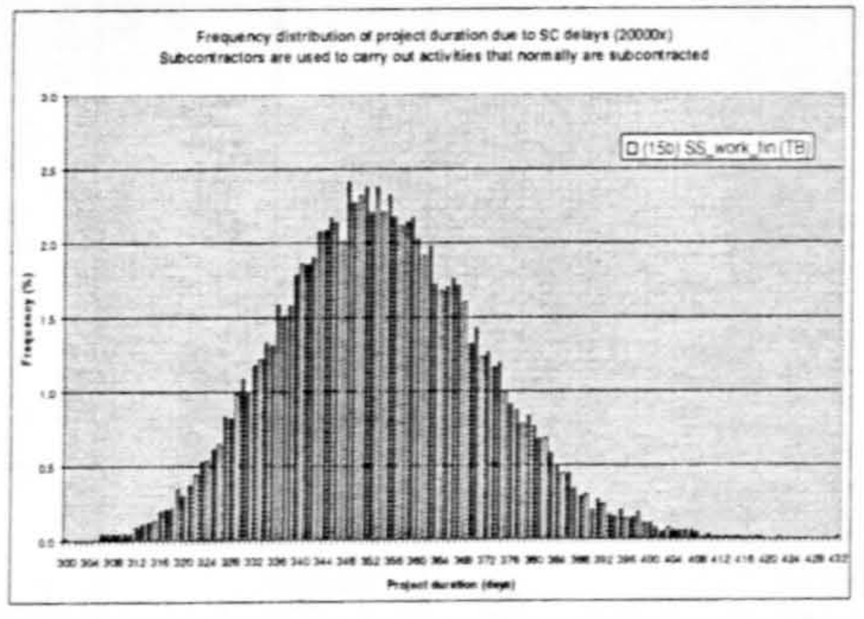


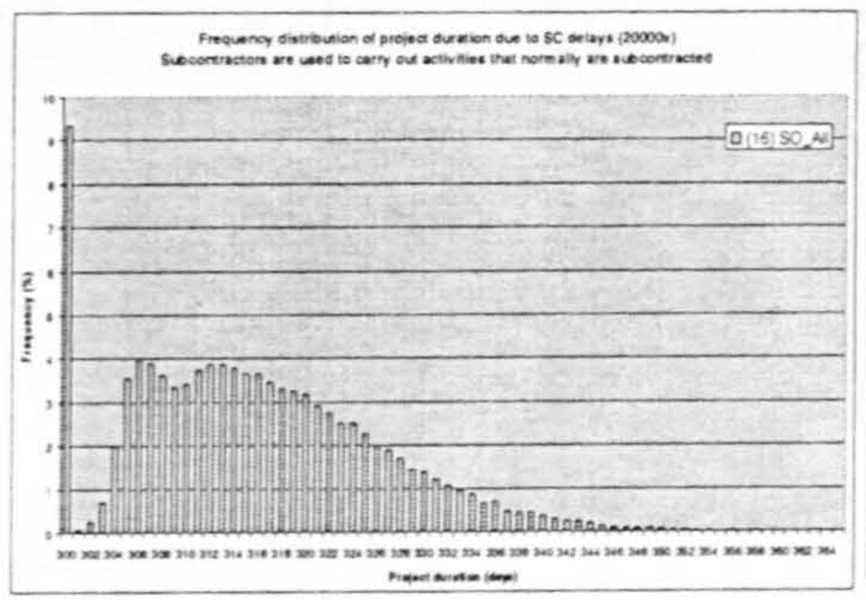


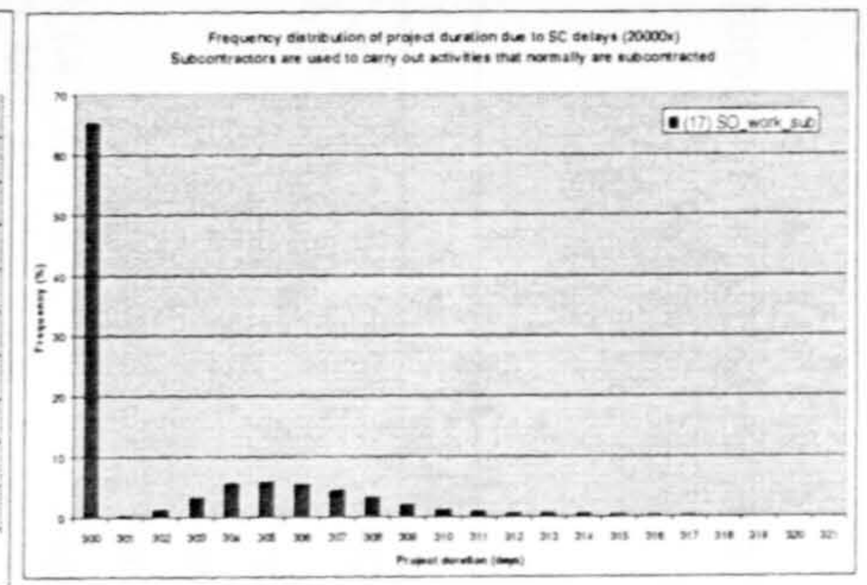


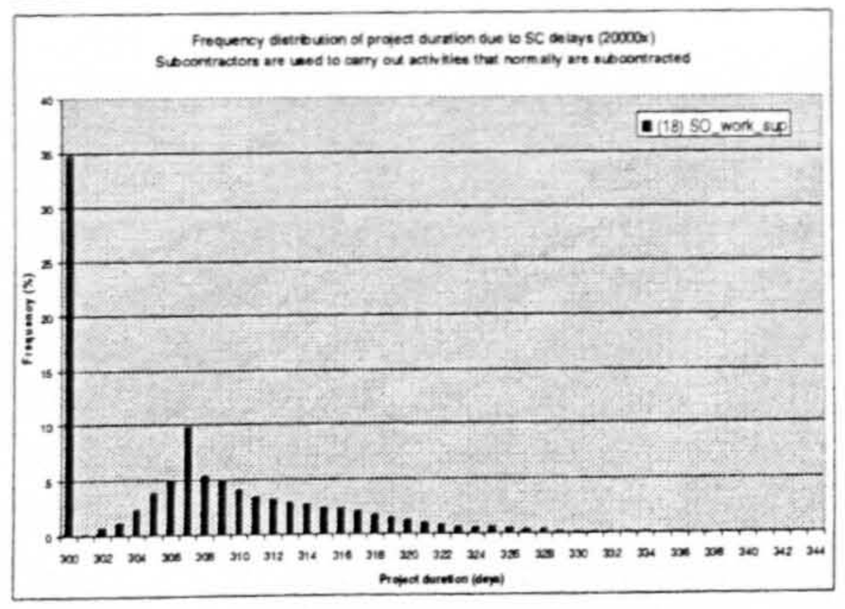
Appendix C3 - Histogram results (continued)

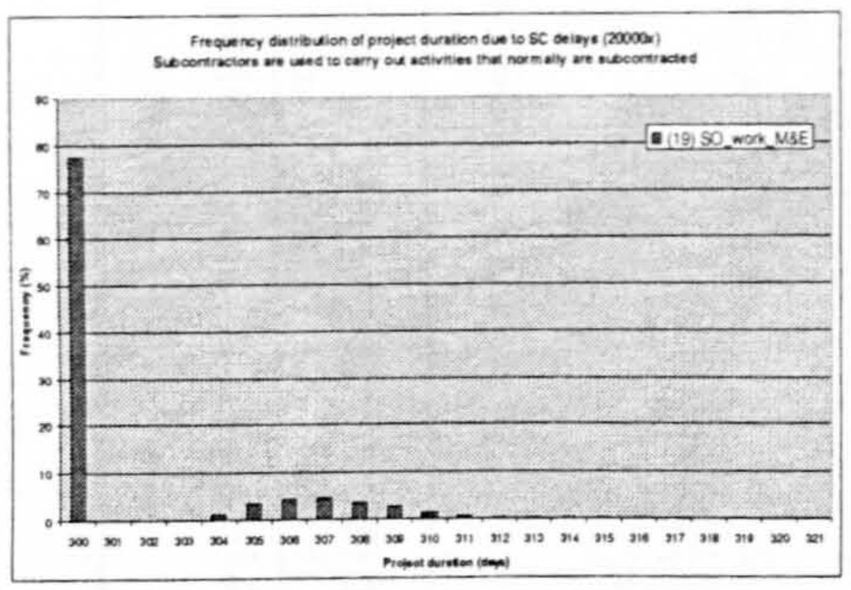


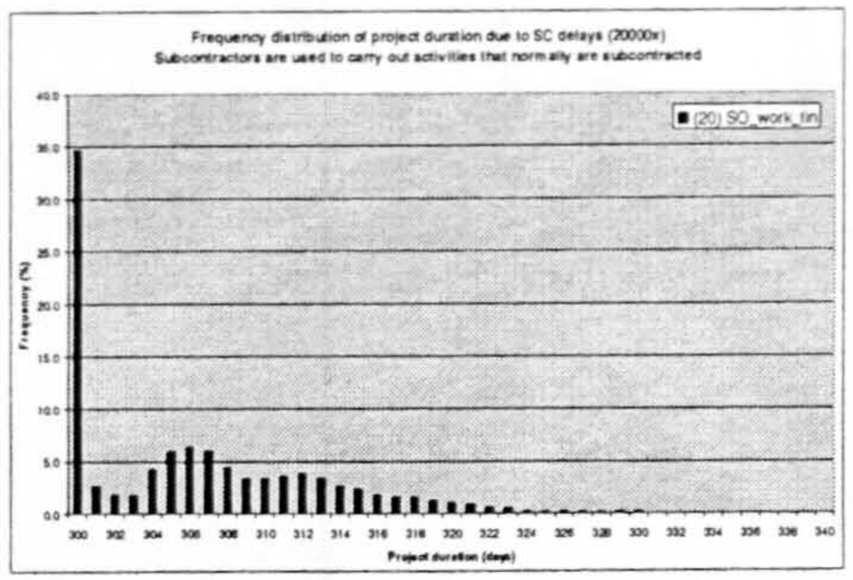












Appendix C4
Wilcoxon signed-ranks test results for model (1a/c) O/P_MC_All (TB) with various data size

Ranks

		N	Mean Rank	Sum of Ranks
(1c) P_MC_All (TB) 100x - (1a) O_MC_All (TB) 100x	Negative Ranks	47(a)	47.51	2233.00
	Positive Ranks	52(b)	52.25	2717.00
	Ties	1(c)		
	Total	100		
(1c) P_MC_All (TB) 200x - (1a) O_MC_All (TB) 200x	Negative Ranks	83(d)	104.17	8646.50
	Positive Ranks	113(e)	94.33	10659.50
	Ties	4(f)		
	Total	200		
(1c) P_MC_All (TB) 300x - (1a) O_MC_All (TB) 300x	Negative Ranks	136(g)	144.61	19666.50
	Positive Ranks	164(h)	155.39	25483.50
	Ties	0(i)		
	Total	300		

a (1c) P_MC_All (TB) 100x < (1a) O_MC_All (TB) 100x
b (1c) P_MC_All (TB) 100x > (1a) O_MC_All (TB) 100x
c (1c) P_MC_All (TB) 100x = (1a) O_MC_All (TB) 100x
d (1c) P_MC_All (TB) 200x < (1a) O_MC_All (TB) 200x
e (1c) P_MC_All (TB) 200x > (1a) O_MC_All (TB) 200x
f (1c) P_MC_All (TB) 200x = (1a) O_MC_All (TB) 200x
g (1c) P_MC_All (TB) 300x < (1a) O_MC_All (TB) 300x
h (1c) P_MC_All (TB) 300x > (1a) O_MC_All (TB) 300x
i (1c) P_MC_All (TB) 300x = (1a) O_MC_All (TB) 300x

Test Statistics(b)

	(1c) P_MC_All (TB) 100x - (1a) O_MC_All (TB) 100x	(1c) P_MC_All (TB) 200x - (1a) O_MC_All (TB) 200x	(1c) P_MC_All (TB) 300x - (1a) O_MC_All (TB) 300x
Z	-.845(a)	-1.266(a)	-1.934(a)
Asymp. Sig. (2-tailed)	.398	.206	.053

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
(1c) P_MC_All (TB) 500x - (1a) O_MC_All (TB) 500x	Negative Ranks	223(a)	240.75	53687.00
	Positive Ranks	272(b)	253.94	69073.00
	Ties	5(c)		
	Total	500		
(1c) P_MC_All (TB) 1K - (1a) O_MC_All (TB) 1k	Negative Ranks	451(d)	468.73	211399.00
	Positive Ranks	533(e)	512.61	273221.00
	Ties	16(f)		
	Total	1000		
(1c) P_MC_All (TB) 2K - (1a) O_MC_All (TB) 2K	Negative Ranks	907(g)	929.19	842779.00
	Positive Ranks	1062(h)	1032.66	1096686.00
	Ties	31(i)		
	Total	2000		

a (1c) P_MC_All (TB) 500x < (1a) O_MC_All (TB) 500x
b (1c) P_MC_All (TB) 500x > (1a) O_MC_All (TB) 500x
c (1c) P_MC_All (TB) 500x = (1a) O_MC_All (TB) 500x
d (1c) P_MC_All (TB) 1K < (1a) O_MC_All (TB) 1k
e (1c) P_MC_All (TB) 1K > (1a) O_MC_All (TB) 1k
f (1c) P_MC_All (TB) 1K = (1a) O_MC_All (TB) 1k
g (1c) P_MC_All (TB) 2K < (1a) O_MC_All (TB) 2K
h (1c) P_MC_All (TB) 2K > (1a) O_MC_All (TB) 2K
i (1c) P_MC_All (TB) 2K = (1a) O_MC_All (TB) 2K

Test Statistics(b)

	(1c) P_MC_All (TB) 500x - (1a) O_MC_All (TB) 500x	(1c) P_MC_All (TB) 1K - (1a) O_MC_All (TB) 1k	(1c) P_MC_All (TB) 2K - (1a) O_MC_All (TB) 2K
Z	-2.416(a)	-3.467(a)	-5.032(a)
Asymp. Sig. (2-tailed)	.016	.001	.000

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
(1c) P_MC_All (TB) 5K - (1a) O_MC_All (TB) 5K	Negative Ranks	2185(a)	2383.36	5207632.50
	Positive Ranks	2745(b)	2530.89	6947282.50
	Ties	70(c)		
	Total	5000		
(1c) P_MC_All (TB) 10K - (1a) O_MC_All (TB) 10K	Negative Ranks	4467(d)	4693.49	20965799.50
	Positive Ranks	5379(e)	5114.52	27510981.50
	Ties	154(f)		
	Total	10000		
(1c) P_MC_All (TB) 20K - (1a) O_MC_All (TB) 20K	Negative Ranks	8875(g)	9396.11	83390487.00
	Positive Ranks	10783(h)	10186.20	109837824.00
	Ties	342(i)		
	Total	20000		

a (1c) P_MC_All (TB) 5K < (1a) O_MC_All (TB) 5K
b (1c) P_MC_All (TB) 5K > (1a) O_MC_All (TB) 5K
c (1c) P_MC_All (TB) 5K = (1a) O_MC_All (TB) 5K
d (1c) P_MC_All (TB) 10K < (1a) O_MC_All (TB) 10K
e (1c) P_MC_All (TB) 10K > (1a) O_MC_All (TB) 10K
f (1c) P_MC_All (TB) 10K = (1a) O_MC_All (TB) 10K
g (1c) P_MC_All (TB) 20K < (1a) O_MC_All (TB) 20K
h (1c) P_MC_All (TB) 20K > (1a) O_MC_All (TB) 20K
i (1c) P_MC_All (TB) 20K = (1a) O_MC_All (TB) 20K

Test Statistics(b)

	(1c) P_MC_All (TB) 5K - (1a) O_MC_All (TB) 5K	(1c) P_MC_All (TB) 10K - (1a) O_MC_All (TB) 10K	(1c) P_MC_All (TB) 20K - (1a) O_MC_All (TB) 20K
Z	-8.704(a)	-11.604(a)	-16.621(a)
Asymp. Sig. (2-tailed)	.000	.000	.000

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

Appendix C5

Comparing subcontractor delays and delays they replaced

All work is carried out by the main contractor							Subcontractors are used in the project				
Criticality	No	(1b) O_MC_All (NTB)	Prob (%)	Most likely (days)	Impact	Total Impact	No	(16) SO_All	Prob (%)	Most likely (days)	Total Impact
Crit	1	START					1	START			
Crit	2	SITE ESTABLISHMENT/ FENCING (PRECAST)					2	SITE ESTABLISHMENT/ FENCING (PRECAST)			
		Late delivery: Precast fencing	10	6	0.6	0.93					
		Skill shortages: Labourer	11	3	0.33						
Crit	3	FORM ACCESS ROAD & REDUCE LEVEL					3	FORM ACCESS ROAD & REDUCE LEVEL			
								SC : Groundwork	8	6	0.48
Crit	4	CONSTRUCT FOUNDATIONS					4	CONSTRUCT FOUNDATIONS			
		Delivery with wrong specs: RM Concrete*	15	2	-	0.4		SC: Foundation	6	5	0.3
		Delivery with insuficient quantity: RM Concrete*	6	1	-						
		Skill shortages: Concrete gang*	10	4	0.4						
Crit	5	ERECT STRUCTURAL STEEL FRAME					5	ERECT STRUCTURAL STEEL FRAME			
		Late delivery: steel frames	9	5	0.45	1.25		SC: Steelwork	8	6	0.48
		Skill shortages: Steel work erectors*	16	5	0.8						
		Shortages: Cranes*	11	6	-						
Crit	6	SUBSTRUCTURE BRICKWORK/BLOCKWORK					6	SUBSTRUCTURE BRICKWORK/BLOCKWORK			
		Difficulty in finding in the market: Bricks/blocks	14	12	1.68	4.37		SC: Bricks/blockwork	11	7	0.77
		Late delivery: Bricks/blocks	7	5	0.35						
		Delivery with wrong specs: Bricks*	9	7	-						
		Materials damaged on arrival: Bricks/blocks*	6	13	-						
		Delivery with insufficient quantity*	15	6	-						
		Skill shortages: Bricklayers*	26	9	2.34						
Crit	7	CONCRETE FLOOR SLAB					7	CONCRETE FLOOR SLAB			
		Late delivery: steel reinforcement	6	4	0.24	0.64		SC: Concrete floor	13	6	0.78
		Delivery with wrong specs: RM Concrete*	15	2	-						
		Delivery with insufficient quantity: RM Concrete*	6	1	-						
		Skill shortages: Concrete gang*	10	4	0.4						
Crit	8	SUPERSTRUCTURE BRICK/BLOCKWORK					8	SUPERSTRUCTURE BRICK/BLOCKWORK			
		Difficulty in finding in the market: Bricks/blocks	14	12	1.68	4.37		SC: Bricks/blockwork	11	7	0.77
		Late delivery: Bricks/blocks	7	5	0.35						
		Delivery with wrong specs: Bricks/blocks*	9	7	-						
		Materials damaged on arrival: Bricks/blocks*	6	13	-						
		Delivery with insufficient quantity: Bricks/blocks*	15	6	-						
		Skill shortages: Bricklayers*	26	9	2.34						
		Shortages: scaffoldings*	25	7	-						
Crit	9	INSULATION					9	INSULATION			
		Skill shortages: Bricklayers	26	9	2.34	2.34		SC: Bricks/blockwork	11	7	0.77
Crit	10	ROOF JOIST/FRAMEWORK					10	ROOF JOIST/FRAMEWORK			
		Late delivery: Roofing materials	4	6	0.24	0.9		SC: Roofwork	16	10	1.6
		Delivery with wrong specs: Roofing materials*	6	10	-						
		Plant shortages: Crane*	11	6	0.66						
Crit	11	ROOF COVERINGS					11	ROOF COVERINGS			
		Late delivery: Roofing materials	4	6	0.24	1.99		SC: Roofwork	16	10	1.6
		Delivery with wrong specs: Roofing materials*	6	10	-						
		Shortages: scaffoldings*	25	7	1.75						
		Skill shortages: Scaffolders*	16	4	-						
	12	FASCIAS & SOFFITS					12	FASCIAS & SOFFITS			
		Delivery with wrong specs: Timber*	12	7	-	1.75		SC: Roofwork	16	10	1.6
		Delivery with insufficient quantity: Timber*	16	5	-						
		Shortages: scaffoldings*	25	7	1.75						
		Skill shortages: Scaffolders*	16	4	-						
	13	WINDOWS & DOORS					13	WINDOWS & DOORS			
		Late delivery: Windows & Doors	11	7	0.77	1.82		SC: Windows & Doors	17	10	1.7
		Delivery with wrong specs: Windows & Doors*	6	12	-						
		Materials damaged on arrival: Windows & Doors*	7	15	1.05						
Crit	14	FLOOR SCREED					14	FLOOR SCREED			
								SC: Concrete floor	13	6	0.78
Crit	15	SUSPENDED CEILINGS GRID - TILES					15	SUSPENDED CEILINGS GRID - TILES			
		Materials damaged on arrival: Ceiling tiles	20	6	1.2	1.2		SC: Roofwork	16	10	1.6
	16	FLOOR TILING					16	FLOOR TILING			
		Difficult to find in the market: Tiles	20	12	2.4	2.4		SC: Finishings & Decoration	14	6	0.84
	17	PARTITIONS					17	PARTITIONS			
		Skill shortages: Joiner	28	7	1.96	1.96		SC: Finishings & Decoration	14	6	0.84
Crit	18	PLASTERWORK					18	PLASTERWORK			
		Skill shortages: Plasterers	27	8	2.16	2.16		SC: Plasterworks	26	11	2.86
Crit	19	JOINERY WORKS					19	JOINERY WORKS			
		Difficult to find in the market: Joinery	10	10	1	2.96		SC: Finishings & Decoration	14	6	0.84
		Skill shortages: Joiners	28	7	1.96						
Crit	20	M & E INSTALLATIONS					20	M & E INSTALLATIONS			
		Skill shortages: Electrician	28	9	2.52	2.52		SC: M&E	12	7	0.84
Crit	21	2nd FIX ELECTRICAL					21	2nd FIX ELECTRICAL			
		Skill shortages: Electrician	28	9	2.52	2.52		SC: M&E	12	7	0.84
Crit	22	DECORATION					22	DECORATION			
								SC: Finishings & decoration	14	6	0.84
Crit	23	FURNISHING					23	FURNISHING			
		Difficult to find in the market: Furniture	32	7	2.24	4.13		SC: Finishings & decoration	14	6	0.84
		Delivery with insufficient quantity: Furniture	21	9	1.89						
Crit	24	FIXTURES & FITTINGS					24	FIXTURES & FITTINGS			
		Difficult to find in the market: Fixtures & Fittings	38	15	5.7	7.66		SC: Finishings & decoration	14	6	0.84
		Skill shortages: Joiners	28	7	1.96						
Crit	25	TEST & COMMISSION					25	TEST & COMMISSION			
Crit	26	FINISH					26	FINISH			
	27	IPS FRAMEWORK/PANELING/VANITY UNITS					27	IPS FRAMEWORK/PANELING/VANITY UNITS			
		Skill shortages: Plumbers	28	8	2.24	2.24					
	28	PLUMBING/SANITARYWARE					28	PLUMBING/SANITARYWARE			
		Skill shortages: Plumbers	28	8	2.24	2.24					
	29	SHOWER CUBICLES					29	SHOWER CUBICLES			
		Materials damaged on arrival: Shower cubicles	5	10	0.5	0.5					
	30	WALL TILING - SHOWER/TOILET AREAS					30	WALL TILING - SHOWER/TOILET AREAS			
		Difficult to find in the market: Tiles	20	12	2.4	2.4		SC: Finishings & decoration	14	6	0.84
	31	VINYL FLOORING					31	VINYL FLOORING			
								SC: Finishings & decoration	14	6	0.84
	32	DRAINAGE WORKS					32	DRAINAGE WORKS			
		Delivery with insufficient quantity: Drainage	23	5	1.15	1.15		SC: Drainage works	4	4	0.16
		Materials damaged on arrival: drainage*	6	3	-						
		Skill shortages: Labourers*	11	3	-						
	33	EDGE KERBING					33	EDGE KERBING			
		Skill shortages: Labourers	11	3	0.33	0.33					
	34	STONE UP & BITMAC FOOTPATHS					34	STONE UP & BITMAC FOOTPATHS			
		Skill shortages: Labourers	11	3	0.33	0.33		SC: Groundwork	8	6	0.48
	35	LANDSCAPING					35	LANDSCAPING			
		Skill shortages: Labourers	11	3	0.33	0.33		SC: Groundwork	8	6	0.48

Note:

* Delays in parallel

- Substructure work
- Superstructure work
- Finishing work
- M&E work